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THE UNIVERSITY OF ALBERTA

SUBSURFACE LATERAL FLOW AND VARIABILITY OF SELECT PEACE RIVER SOILS

by

© DONALD DOUGLAS HARE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

IN

SOIL PHYSICS

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

FALL 1986

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Date September 20, 1986

ABSTRACT

Quantification of the individual components of soil water flow processes is important in the development of a thorough understanding of water movement in soils. Furthermore, an inability to quantify individual components leads to a vague or often oversimplified total flow value, which limits its use in flow related investigations.

Due to the heterogeneity, anisotropy, and site spatial and temporal variability of soils, site specific data or component values of soil water flow regimes cannot be transposed directly to different locations. A field approach that includes the determination of soil physical properties that influence flow components, and that also permits characterization of the variation of these properties, is required to permit extrapolation of information on flow components to other sites.

The objective of this study was to evaluate soil physical property variability and a lateral soil water flow component on sloped agricultural land. The null hypothesis tested was that soil water status was not a function of location on a co-ordinate grid. The specific objectives of this study were: 1) quantification of the variability of selected soil properties, 2) determination if a significant subsurface lateral flow component existed on sloped agricultural land, and 3) evaluation of this component, if it existed.

In 1983, a field study was initiated in the Peace River region of Alberta to evaluate selected soil physical properties and to quantify the subsurface lateral flow component on sloped agricultural land. At each of the two sites, La Glace and Berwyn, 16 and 12 infiltration determinations, respectively, were conducted using concentric infiltration rings. Evaluations included gravimetric sampling of an area around the infiltration ring on a predetermined pattern to analyze moisture redistribution, soil physical and moisture variables, and to determine both small scale variation (less than six m^2) and field scale variation (500 and 1800 m^2) in soil properties. Soil properties investigated included: texture, field moisture content, bulk density, moisture retention at -33 and -1500 kPa, and available water capacity.

Results indicated that, in general, coefficient of variation (CV) increased to a maximum at a certain depth, then decreased. A field average of all properties for each depth indicated that certain depths were more variable than others. Variation of soil properties, as measured by CV, increased as the size of the sample area increased, and varied between the two sites. The number of samples required to estimate the mean within 10% for soil physical properties varied from two to ten samples for the grid scale, and from two to twenty-six samples for the field scale. In general, as sample area increased, a larger number of samples was required to estimate the mean at the same level of

precision.

The presence of a subsurface lateral flow component was confirmed by statistical analysis. The soil water status null hypothesis was not accepted in 85% of the depths at both sites. The subsurface lateral flow component was determined to be 7.9 to 37.7% of the added water. These values should be transferable to other Peace River locations with comparable soil variability and site characteristics.

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I. INTRODUCTION

Dr. Harry Hill, Director-General of the Prairie Farm Rehabilitation Administration, speaking on the subject of water on the prairies, made the following observations:[1]

> "Firstly, we must generate a conservation ethic which will ensure, as far as possible, the soil and water resources are renewable and available in a non-degenerated state for the use of future generations. Management of our water resources for dryland agriculture must be innovative, highly researched and integrated with knowledge of the soil resource. We must also think of the soil resource in association with the water resource. The two are interdependent and cannot be separated."

In agriculture, soil and water utilization is interdependent and inseparable. Water, or more specifically, a limited supply of water, is the major limiting factor to dryland crop production today (Staple and Lehane, 1952). They predicted that 16-22 cm of moisture are required to grow a cereal grain crop and that half of the moisture must be present in the soil at the time of seeding. Intensive crop management production systems, currently used in agriculture, require optimum allocations of resources, and an in-depth technical understanding of the soil-water regime and the soil-water-plant interface. Prediction of soil water reserves has become paramount in agriculture today because of the high-input-high-output requirements of these production systems.

The ability to predict and understand the consequences of the soil and water resource interactions has also become

---

[1]H.Hill. 1981. Water on the prairies. Canada Grains Council. Proceedings, October, 1981. Pp. 41-44.

a national interest, fueled by recent environmental concerns such as hazardous waste disposal in soil, toxic chemical spills on soil, seepage of toxins into water supplies; and agricultural concerns such as pesticide contamination of groundwater, accelerating soil erosion and salinity, and major droughts.

As a result of these agricultural and environmental needs and concerns, a resurgence of national interest in applied research has occurred, primarily in soil hydrological and soil conservation studies. Not only must the fundamental physical processes of soil-water resource interactions be completely understood, but these interactions must be quantifiable and transferable to other sites and situations.

Quantification of soil water flow processes is difficult, because the hydrologic cycle is a complex, dynamic, highly interactive cycle. Flow of water in soils can be predicted by the empirical equation known as Darcy's Law, and is driven by hydraulic gradients or differences in energy potential. Infiltration, the transmission rate, and the eventual fate of water in soil is dependent upon numerous soil factors, moisture conditions, and slope characteristics. Infiltration and moisture redistribution are very complex processes with spatial and temporal variability, heterogeneity, and anisotropy directly resulting in measurement uncertainty, and a lack of direct field observations of these processes. Researchers involved

in interpretation or site comparisons, even when an apparently homogeneous soil is present, must preferably either measure the range of variation, or at least accept the probability that the quantity measured will have similar variability to that present in other studies.

Currently, field soil water flow processes are not completely understood primarily due to measurement difficulties, spatial and temporal variability, and a lack of direct field measurements and observations. Quantification of the actual flow components and processes is not limited necessarily by the lack of understanding of the flow processes but rather in the transferability of results to other sites, due to the lack of specific on-site variability characterization. Specific variability often necessitates a complete re-investigation of every site, or at least the acceptance that the variation of flow influencing variables is similar at other sites. More research which focuses on the characterization of variability of both soil flow components and soil physical properties simultaneously is necessary.

Of all soil-water flow components, one component in particular has been difficult to quantify - the subsurface lateral flow component. The subsurface lateral flow component has been defined as that part of lateral flow that infiltrates the surface and moves laterally through the upper soil horizons as unsaturated flow or as perched saturated flow above the main ground water table (Freeze,

1972). The evaluation of subsurface lateral flow is an integral part of any hydrologic study, and the recent research interest in this component simply underscores its significance in soil-water flow studies. Recent papers by Pilgrim and Huff (1978) and McCarty and Walters (1982) suggest that the subsurface lateral flow component may be a key component to evaluate in soil moisture and soil erosion studies.

In 1983, a study was undertaken to evaluate soil variability and the subsurface lateral flow component in selected soils. In selecting a site, the Peace River region was chosen, because this area has been identified as a region that generally experiences very large soil erosional events, has large, intense moisture events, and could experience significant lateral flow of subsurface moisture. Also the Peace River region was selected because it represents nine million hectares of the 11 million hectares that are potentially arable soils in northern Canada; currently, about 2.7 million hectares in the Peace River region are used for agricultural production (Bailey, 1981).

The Peace River region is a geographically unique agricultural region as it is located further north than most agricultural regions in the world. The Peace River region is the northen extension of the North American Great Plains, and is located in northern Alberta and north-eastern British Columbia (Pettapiece and Lindsay, 1981). It is between 54° and 59° latitude, and is within the boreal forest ecosystem

(Bailey, 1981).

Since the Peace River region is located more northerly than most other agricultural regions in the world, climatic stresses can be acute. Chanasyk et al. (1983) examined climatic, pedological, and hydrological factors to determine if the Peace River region was unique compared to the rest of Alberta. They concluded that the agricultural problems in this region appear to be the result of unfavorable interactions of climate, soils, and hydrology. The major significant climatic difference is low evaporation in September and October, resulting in a moisture surplus which can lead to trafficability problems during harvest, as well as delays in fall land preparation for the subsequent crop season.

Soils in the Peace River region have generally developed on glacio-lacustrine materials. Both Solonetzic and Luvisolic soils orders are present, with many Solonetzic subgroups of the Chernozemic and Luvisolic orders (Chanasyk et al., 1983). The fact that these particular orders and subgroups of soils have developed on saline, fine textured materials does not make these soils unique in Alberta, but their development on such materials with a uniformly high clay content over a very large geographic area does (Chanasyk et al., 1983). Because of the generally fine texture of the surface horizons (50-60% silt and up to 25% clay), the large amount of water available infiltrates very slowly, primarily because of high water holding capacities

of the A horizon, and the very slowly permeable B horizon, characteristic of Solonetzic and Luvisolic soils. The result is a nearly saturated soil surface during periods of excess moisture (spring and fall), increasing the potential for farming operation delays, runoff and erosion of soil.

Canadian prairie soils, and especially the Peace River region soils, possess several major characteristics necessary and conducive to the creation of subsurface lateral flow. The soil surface horizons often have high silt percentages, large available water holding capacities, and low densities. The B horizons are generally two to four orders of magnitude lower in hydraulic conductivity, resulting in a slowly permeable layer near the surface. In addition, steep convex slopes, large volumes of water during springmelt, and intense, short-duration precipitation events can occur, resulting in saturated soil surface conditions. Studies indicate that the subsurface lateral flow component on sloped land can be the dominant single flow component, often representing 12-50% of total flow, and usually occurring in a zone above a flow-impeding layer (Chanasyk, 1980).

Therefore, because of the importance of subsurface lateral flow in hydrologic studies, and the presence of many of the major contributing factors to subsurface flow being present in Peace River soils, a field study was conducted. The objective of the study was to evaluate the variability of soil physical properties and the subsurface lateral flow

component for selected Peace River soils. To evaluate moisture redistribution adequately, the following objectives were identified:

1. Quantitatively evaluate the variability of selected soil physical properties,
2. Develop and perform a field investigation to determine if a significant subsurface lateral flow component exists on sloped agricultural land, and
3. If a significant subsurface lateral flow component exists, evaluate the extent of the component.

The null hypothesis for this field study was that soil water status is not a function of location on a coordinate grid.

II. LITERATURE REVIEW

The interaction of the hydrosphere, atmosphere, biosphere, and geosphere is called the hydrologic cycle. The major components of this cycle are schematically conceptualized in Figure 1. The study of the hydrologic cycle is multidisciplinary in nature. It encompasses chemistry, physics, geology, hydrology, soil science, meteorology, and engineering.

Soil water studies are related to disciplines that are based on fundamental physical processes of flow through porous media. Soil physics is a unique and complex application of fluid mechanics, because:

1. soil is a semi-solid matrix,
2. soil matrix properties vary with relation to climate, vegetation, topography, aspect, temperature, and time,
3. heterogeneity, anisotropy, and spatial and temporal variability are the rule, and
4. soil water flow is generally in the unsaturated state.

A. SOIL WATER FLOW

Elemental Unit

The unit represented in Figure 2 forms a basis for soil water study. This representative elemental unit volume, sometimes referred to as an elemental control volume, represents the basic soil unit. It can be analogous to the

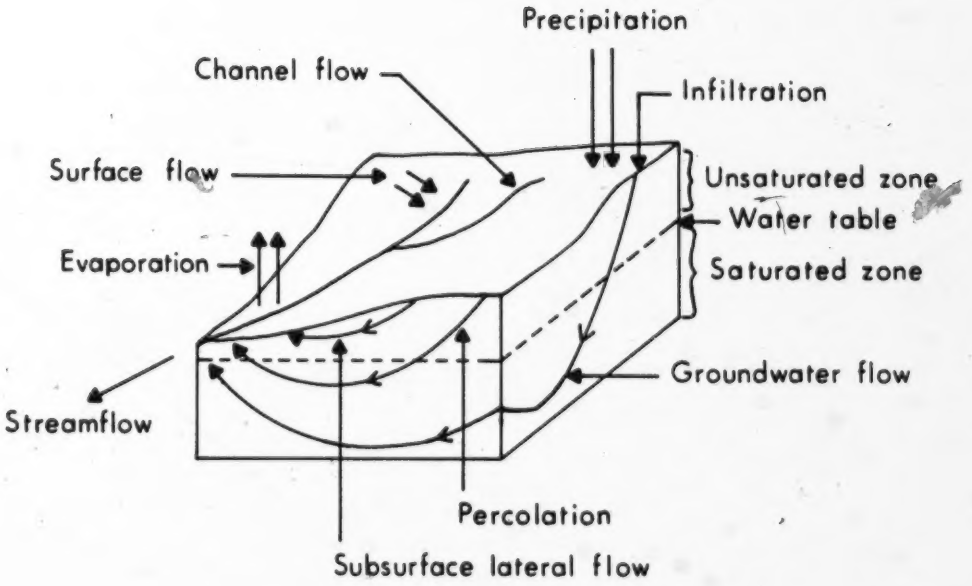


Figure 1. Schematic representation of the hydrologic cycle (Adapted from Freeze and Cherry, 1979).

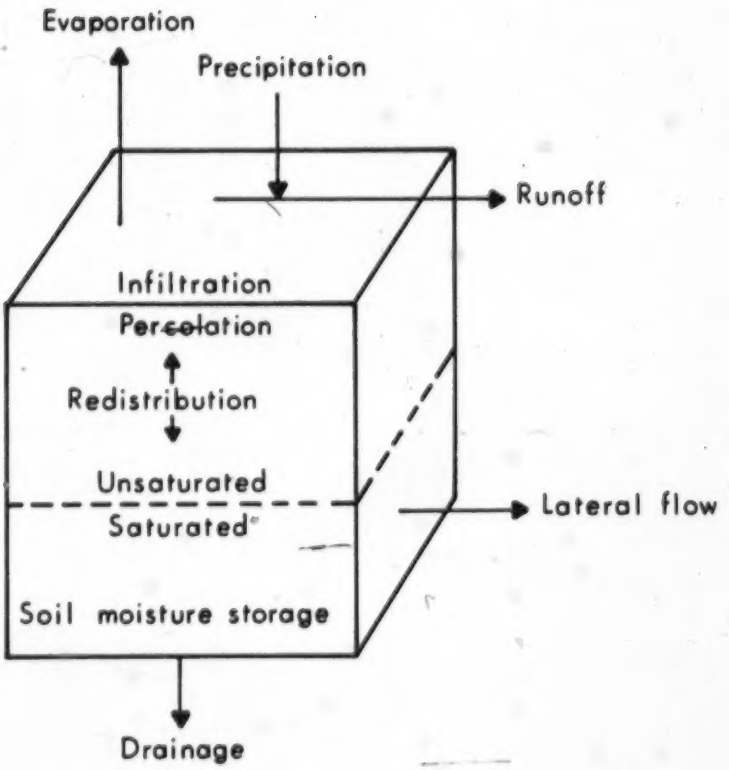


Figure 2. Elemental unit of soil water processes (Adapted from Freeze and Cherry, 1979).

pedon concept used in soil classification and genesis. This representative unit has many of the processes occurring in it that occur in the soil as a whole. With the principles of similitude, and with the advent of numerical and finite-difference computer analysis, this elemental approach allows soil water flow analysis to be more manageable.

Differentiation of this elemental unit is an important first step for flow analysis, because the law of conservation of mass for steady-state flow through a saturated porous medium requires that the rate of fluid mass flow into any elemental control volume be equal to the rate of fluid mass flow out of that elemental control volume (Freeze and Cherry, 1979). By further extension of the laws of energy, similar situations must be true for unsaturated conditions.

Major soil water flow processes and components as outlined in Figure 2 are present in both the elemental unit and the soil as a whole.

Soil Water Flow

Fundamental to soil-water flow processes is the empirical relationship between medium and fluid, known as Darcy's Law. In 1856, a French engineer, Henry Darcy, published his report on the water supply of the city of Diijon, France (Freeze and Cherry, 1979). The results of his experiment have been generalized into the empirical law that now bears his name. This law, based on experimental evidence

only, forms the basis of studies of flow through porous media and is widely used in numerous fields of study, including soil science, hydrogeology, and petroleum engineering.

Many attempts have been made to derive both Darcy's Law and field flow equations from fundamental physical laws, but few attempts have been successful (Freeze and Cherry, 1979). Examples of such attempts includes the work of Childs and Collis-George (1950), Marshall (1958), and Millington and Quirk (1959). Kunze et al. (1968) concluded that derived equations only have general applications within the limitations imposed in their derivation; principally isotropy, restrictions placed on pore geometry and length, and the ignoring of such phenomena as air entrapment. Darcy's Law has numerous limitations for the prediction of field flow rates (Klute, 1971), but as a first approximation, Darcy-based flow equations are sufficiently valid for predicting most unsaturated flow behaviour. While other equations can be accurate, under controlled or simplified conditions, few have been derived that are as universally adaptable to a field flow situation as the empirical Darcy equation.

Darcy's Law

Considering the apparatus illustrated in Figure 3, when water is forced into one end, water flows through a medium (sand in Darcy's experiment) and exits at a discharge rate

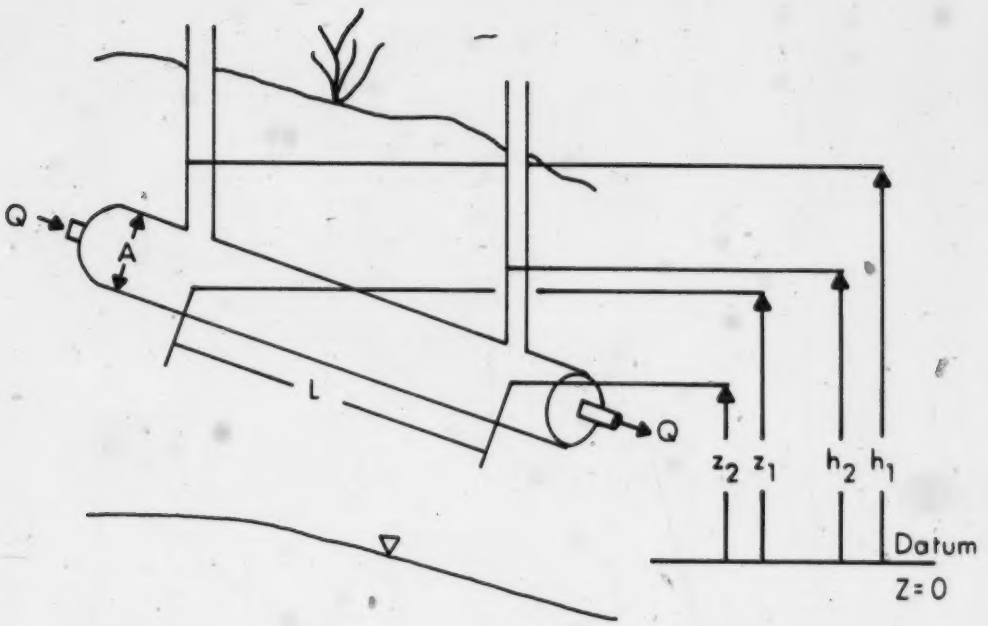


Figure 3. Experimental apparatus for the illustration of Darcy's Law (Adapted from Freeze and Cherry, 1979).

Q. There is an energy loss of h_1-h_2, over distance L, because work was required to overcome the frictional forces of water moving through the soil. In this process, an irreversible transformation has occurred, where mechanical energy is turned into thermal energy, as described by the Bernoulli equation, the classical formulation of energy loss during fluid flow (Freeze and Cherry, 1979). Darcy also found that:

1. $Q \propto h_1-h_2$, discharge is proportional to energy loss,
2. $Q \propto A$, discharge is proportional to cross-sectional area, and
3. $Q \propto 1/L$, discharge is inversely proportional to flow length.

Combining,

$$Q \propto \frac{A(h_1-h_2)}{L} \qquad (1)$$

Where: Q - discharge rate (m^3/s),

A - cross-sectional area (m^2),

h_1, h_2 - hydraulic head, (m), and

L - length between h_1 and h_2 (m).

Darcy found that the constant of proportionality was a property of both the medium and the fluid, and named it hydraulic conductivity. Current forms of the Darcy equation include:

Standard Form: $$Q = \frac{KA(h_1-h_2)}{L}, \qquad (2)$$

Differential Form: $$Q = \frac{Kdh}{dL} A, \qquad (3)$$

Compacted Form: $Q = -KiA$, (4)

Where: $i = \frac{dh}{dL} = \frac{h_2 - h_1}{L}$.

In summary, Darcy's Law states that the flow of a fluid through a porous medium is at a rate proportional to the driving force (hydraulic gradient), and proportional to the properties of the fluid and medium (hydraulic conductivity).

Hydraulic Head

Any flow in nature is energy driven - this is stated in the first law of classical thermodynamics (Van Wylen and Sonntag, 1976). Hydraulic head is the point measure of the energy that water possesses in a flow system, and describes the energy that is available to move water in such a system.

Hydraulic head is composed of two components, a pressure head and an elevation head. It is described by the equation:

$$h = P + Z \quad (5)$$

Where: $P = \frac{P'}{\rho g}$

P' equals the pressure per unit area, ρ is the density of the fluid, g is acceleration due to gravity, and Z is the elevation above a chosen datum.

Thus, Z is the gravitational energy of the system, and represents the work required to move a unit mass of water from the datum to point Z. P is the pressure head and represents the energy the water has available to raise it above a point, or the work the fluid is capable of doing

because of its sustained pressure.

In field studies, the device for measurement of pressure head is a piezometer. Hydraulic head is measured as the height that a column of water rises above the base of the open pipe, plus the elevation of the base of the pipe above a datum - usually either the water table or sea level.

Therefore, the hydraulic head is the measure of energy at a point. If there is an energy gradient between two points, the water will flow from the area of high potential to the area of low potential. This gradient has been termed hydraulic gradient, and is the head difference between the two points, divided by the distance between the two points. Thus, hydraulic gradient is the driving force for water movement, and water will move until the hydraulic gradient is zero.

Hydraulic Conductivity

Hydraulic conductivity is the ratio of the flux (Q/A) to the hydraulic gradient. It is influenced by both the medium and the fluid, and therefore the rate of flow, given equivalent gradients, is a function of the properties of soil, including both soil matrix components and their spatial orientations. Soil factors that influence hydraulic conductivity include texture, structure, density, porosity, pore size, and pore geometry. Fluid factors influencing hydraulic conductivity are viscosity and density, often assumed to be constants in soil water flow calculations

(Hillel, 1971).

Hydraulic conductivity is also influenced by moisture content of the soil. It is a maximum when the soil is saturated, and virtually zero when the soil is dry. When a soil is saturated, all the water conducting pores are filled, resulting in a large, nearly continuous cross-sectional flow area. Conversely, when a soil is unsaturated, a portion of the flow-conducting pore pathway is filled with air, resulting in large decreases of the flow cross-sectional area. In addition, the first pores to empty are the largest pores, which represent the major flow pathway. Under unsaturated conditions, water is forced to move through smaller pores, which are often more tortuous and discontinuous and as a result, less conductive (Hillel, 1971). A transition from an unsaturated to a saturated portion of the soil profile will often be marked by very large increases in hydraulic conductivity.

Natural phenomena, including worm channels, root channels, and cracking soils, can have very large influences on hydraulic conductivity. Quisenberry and Phillips (1976), Thomas and Phillips (1979), Bouma et al. (1982), and Sichinga (1982), found larger flow rates existed in soils when macropores were present than were expected and predicted. These factors emphasize the empirical nature of soil hydraulic conductivity measurement. It is often difficult to determine a constant value of hydraulic conductivity, and usually field measurement and laboratory

measurement will result in vastly different values, occasionally by several orders of magnitude.

Another factor that can affect hydraulic conductivity is the horizon sequence and textural orientations within and between the horizons. Due to genetic processes, soils can contain horizons with very distinct and different textures, structures, and densities. The processes of illuviation and eluviation can result in abrupt changes in clay or silt content in a narrow zone in the soil. Simple depositional processes in the parent material can result in any number of textural discontinuities in the profile. Average profile hydraulic conductivity can be very different from any one individual horizon value.

O'Neal (1949) found that fine-textured, platy, and prismatic soils generally have low saturated hydraulic conductivities. He also found that structure, as well as the relationship between the length of the vertical and horizontal axis of the structural aggregates, influence hydraulic conductivity. The overlap of the aggregates results in the hydraulic conductivity being higher in the direction of the overlap (O'Neal, 1949).

Freeze and Cherry (1979) also emphasized that the orientation of the particles is particularly important to flow and hydraulic conductivity. They state that a ten-fold reduction in hydraulic conductivity will result in decreased flow, which effectively acts as an impermeable barrier to flow between the two layers. On the Canadian prairies, the

hydraulic conductivities of the A and B horizons often vary by 10^{-3} to 10^{-4} cm sec^{-1} or by 2 to 4 orders of magnitude (Freeze and Cherry, 1979).

The presence and identification of transitional and discontinuous areas in profiles is very important to soil water flow studies. Selim et al. (1975) examined the effect of hydraulic conductivity variation on flow patterns for a two dimensional multi-layer hillside seepage problem, using an analytical solution. They found that when a 10 fold reduction in hydraulic conductivity occurred in a lower layer, 90% of the flow occurred in the upper layer as lateral flow. Other combinations were investigated, and it was concluded that a permeable layer near the surface will carry the majority of the flow as lateral flow, when underlain by a less permeable (10-fold reduction) layer.

In prairie soils, there is often a flow-dominating impermeable zone near the surface of the soil. This characteristic can become much more important in determining flow if the soil is on a slope. The impermeable layer will restrict the flow of water into the profile, and as the water builds up, potential energy and positive pressure head will force the water to move downslope. The added water moving downslope increases the potential and pressure of the next elemental unit it enters. Eventually, if the conditions are right and the moisture continues to enter from upslope, overland flow, surface runoff, and soil erosion can occur. This process (Figure 4) has been described by Chanasyk

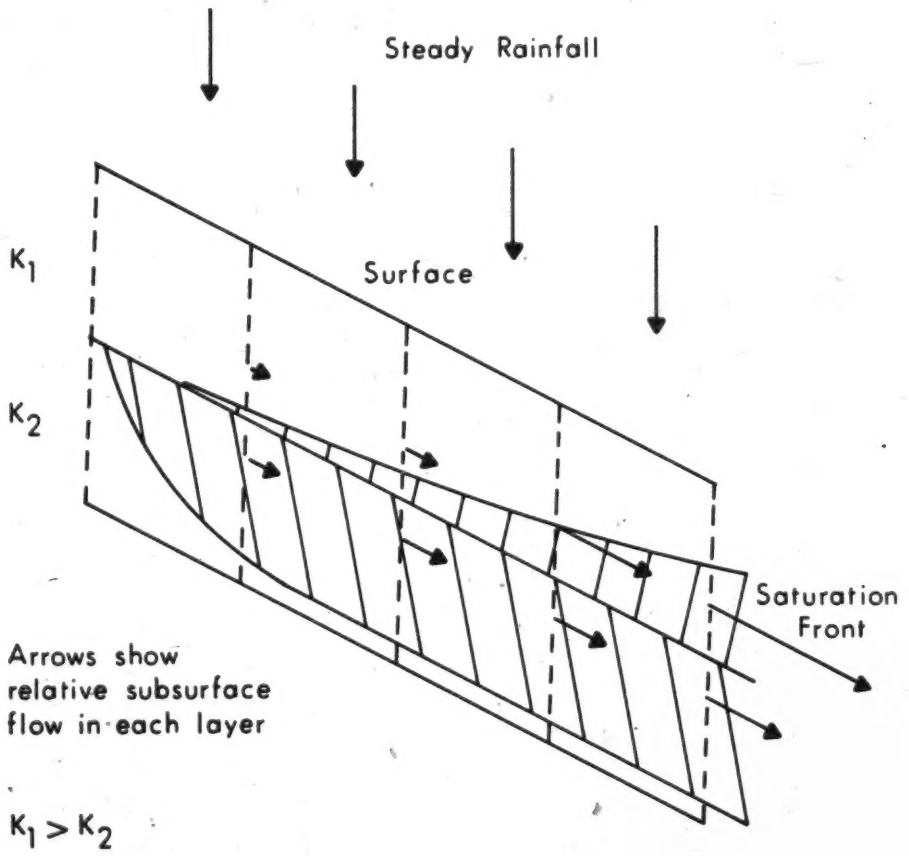


Figure 4. Formation of a saturated layer at an impeding layer (Whipkey and Kirkby, 1978).

(1980), and is supported by the data reported by Day and Luthin (1953), (Figure 5).

Hydraulic conductivity can vary within a zone or horizon over an area. This spatial variation is known as anisotropy, which can be present in a homogeneous or a heterogeneous soil horizon. There are numerous reasons for anisotropy, but horizonation from deposition of parent material, genetic weathering, and illuviation and eluviation of organic matter, sand, silt and clay; soil erosion, and clay orientation are some of the major factors (Freeze and Cherry (1979). In clays and shales horizontal hydraulic conductivity (Kx) is greater than vertical hydraulic conductivity (Kz) by 3:1 to 10:1 because of clay mineral orientation; while, because of horizons and layering, horizontal conductivity in soils is greater than Kz by 10:1 to 1000:1 (Freeze and Cherry, 1979).

Hydraulic conductivities of the entire profile and individual horizons of that profile can be different, especially if large discontinuities exist at the horizon interfaces. The overall hydraulic conductivity of the entire profile is often a function of the least permeable zone in the soil under saturated flow conditions (Luthin, 1978).

Because of the many factors affecting hydraulic conductivity, it is one of the most dynamic, complex phenomena found in nature. Hydraulic conductivity values can vary over 16 orders of magnitude, and in soil will often range up to 8 orders (Freeze and Cherry, 1979). All the

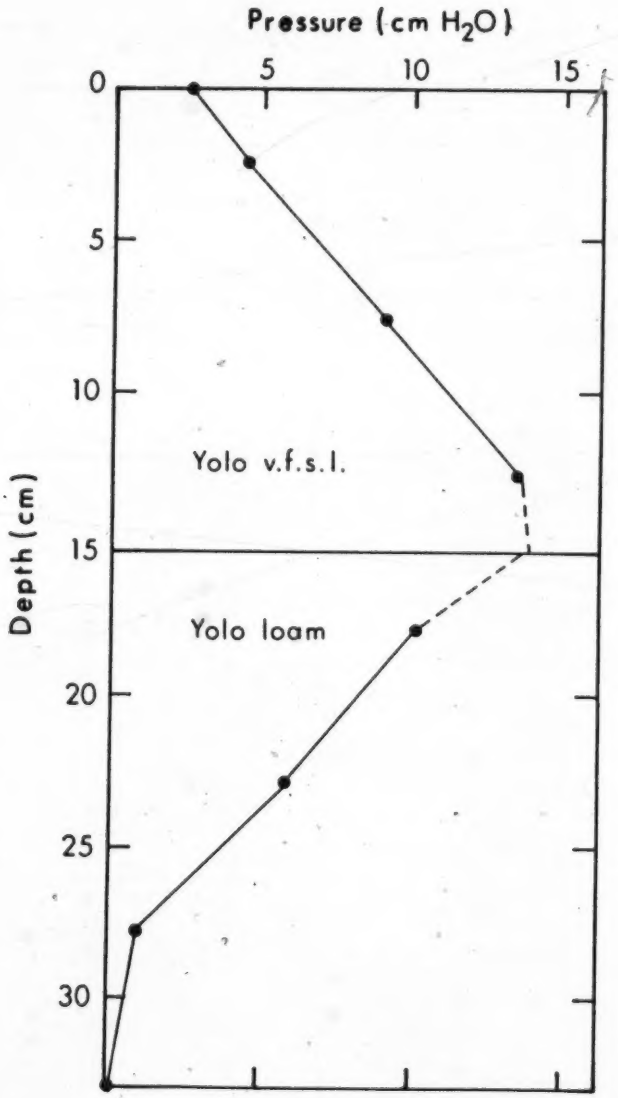


Figure 5. Experimental verification of pressure buildup at a soil discontinuity (Day and Luthin, 1953).

factors affecting hydraulic conductivity are important in flow determinations, and alteration of one or more of the factors, either naturally or mechanically, can have very large influences on flow rate. Also, it follows, and is expected, that a given soil will have varying rates of flow during the course of a year, depending on environmental conditions and soil conditions.

Infiltration

Water input into the soil comes primarily from precipitation. The entrance of water into the soil is termed infiltration.

At the soil surface, water is divided into:

1. surface flow (overland flow, runoff), if the water does not enter the soil at this point, or
2. soil moisture recharge and possibly subsurface flow (groundwater) when it does enter the profile at this point.

Horton (1933) stated that the soil has a critical infiltration limit, and that at precipitation rates above this limit, water will run off, while at rates below this limit, all water will infiltrate. Infiltration rate is not constant with time, and it will vary with soil moisture conditions, decreasing as the soil becomes wetter, eventually reaching a constant minimum level.

Thus factors that influence infiltration rate include:

1. initial moisture content,

2. hydraulic conductivity,
3. surficial conditions of the soil, including roughness and vegetation, and,
4. presence of less permeable, flow impeding layers in the soil profile.

Several researchers have studied why infiltration rate decreases with time. Hillel (1971) proposed the following:

1. there is a decrease in hydraulic gradient, due to the increase in matric potential as the moisture content increases,
2. blocking of pores, either by breakdown of aggregates, washing in of fine clay, or crusting of the surface,
3. swelling of clays to block cracks and large channels in the profile, or
4. air entrapment, where air cannot escape and blocks off the conducting pathways of larger pores.

After water has infiltrated the surface, it is deemed to be percolating through the profile. Soil water can take a variety of pathways, many dependent on the actual conditions in the soil at that particular time. Hydraulic gradient and hydraulic conductivity will determine the rate at which movement will occur, while antecedent moisture conditions and amount of water available will influence the fate of water. As an example, a gentle rain may slowly infiltrate and percolate deeply into a dry soil, whereas an intense rainstorm may quickly saturate the soil only a few centimeters, and then begin to move laterally.

Redistribution

The study of soil water redistribution is very complex, primarily due to lack of direct observations, measurement difficulties, and spatial variation within profiles. Pilgrim and Huff (1978) noted that subsurface storm flow or interflow is both complex and not fully understood. Often, this component is assumed to be negligible at shallow depths. The concept that infiltrating water will move as a wetting front, as first described by Bodman and Coleman (1944), is considered to characterize flow at a point, under field conditions. Often, however, the actual measured flow in the field cannot be accurately described because of the large spatial variability existing in soil physical properties and flow components.

A current school of thought that appears to be evolving regarding flow in field conditions is a two component approach.. One part of the flow is through macropores, cracks, and channels, while the remainder is through the bulk soil matrix. This two component theory is supported by pore stain micromorphometric work (Bouma et al., 1977) and macropore studies (Quisenberry and Phillips, 1976). Chanasyk (1980) referred to the concept of conductivity coefficient rather than hydraulic conductivity, to represent the transmission rate of soils containing cracks or channels. Chanasyk (1980) suggested that this term would include all possible sources of water conduction, other than just the soil regular pore space. Clearly an alternative concept is

necessary to help explain field flow processes that differ from classical Darcian flow. Pilgrim and Huff (1978) used a combination of three major flow process concepts (Horton infiltration, overland flow, and rapid subsurface flow) to help explain why storm waters were detected downslope in the soil after 40 minutes, instead of the 170 hours predicted and calculated according to Darcian theory.

B. SUBSURFACE LATERAL FLOW

Whipkey (1965), studying subsurface stormflow from forested slopes, suggested that the presence of four primary conditions contributed to interflow. These were:

1. sloping land,
2. permeable soil surface,
3. water impeding layer near the surface, and
4. saturated soil.

The first three conditions easily can be found in Peace River and Canadian prairie soils. Saturation can frequently occur during springmelt, or after intense rainstorms, both common to the Peace River region and Canadian prairie soils.

Researchers have shown that lateral flow can be a very large portion of total flow, especially and primarily in zones at or above an impeding or impermeable layer. Chanasyk (1980) reviewed and summarized the following four studies.

Hursh and Hoover (1941), studying flow on a 20% sloped forest soil, found that 12% of all moisture flow was

accounted for at the bottom of the A horizon. Van't Woudt (1954), studying interflow on a 62% sloped volcanic ash, found a buildup of moisture in the A horizon, which resulted in lateral flow. Whipkey (1965), studying flow on a 28% slope in mixed oak stand found that 64% of all flow was above a flow impeding layer. Harr (1977) studied flow on a complex, convex slope, ranging from 50% near the ridge to 110% adjacent to the stream. He found that channel interception and subsurface flow averaged 38% of the gross precipitation, ranging from 23 to 51%. Channel interception was never more than 4%.

Chanasyk (1980) also reported evidence confirming a fifth condition that contributed to interflow, in addition to Whipkey's initial four. He stated that slope shape is important in determining flow potential and investigated three slope shapes - convex, straight, and concave. He stated that because concave slopes would be characterized by water being retained in lower slope positions, less precipitation would be required to recharge the lower position slopes and discharge may occur sooner on concave slopes. Conversely, because slopes would be higher near outflow positions for convex compared to concave slopes, discharge is generally greater for a convex slope. Thus slope shape is a very important factor determining lateral flow potential for a given site.

Field Measurement Of Subsurface Lateral Flow

Tracers offer very good potential for the study of lateral flow. In their pilot study of both surface and subsurface flow, Pilgrim and Huff (1978) used tracers and concluded:

1. tracing can provide information on physical processes that cannot be readily obtained by other means,
2. frequent field measurements of activity profiles provide more useful information on overall processes than do precise laboratory measurements of a small number of samples collected at few sites, and
3. spatial activity surveys were very useful in providing overall patterns of movement of the tracer.

Dyes also have been used extensively in flow pathway work. Reynolds (1966) studied twelve fluorescent dyes for their suitability for tracing water percolating through soils. Corey (1968) studied eight non-fluorescent dyes. Both authors found several dyes that could be used in flow studies, but both authors agreed that the flow of dyes is not the same as water flow, and that results using dyes are more qualitative than quantitative in nature. As an example, Reynolds (1966) found only 1-2% of the dye in very large amounts of leachate from 18 cm columns. Discrepancies in the traced flow regimes occur due to anionic and ionic complexing of ions with soil water, soil water chemistry variability and soil matrix particles influences.

However, recent interest in dyes has been expressed by researchers using micromorphometric techniques. Bouma et al. (1979), using thin sections, analyzed flow pathways through soils to determine the size, number, and volumes of pores that are contributing to flow.

One of the more valuable tools in hydrological studies is radioactive tracers. Radioactive tracers are the best tracers that meet criteria necessary for groundwater tracing. They can be chemically and physically similar to the substance (water) being traced, their introduction does not appreciably disturb the system, they are easily measurable within the system, and their degradability and longevity can be compatible with the experimental design (IAEA, 1976).

Several examples of radioactive tracing used in hydrologic studies include Pilgrim and Huff (1978), Lignon et al. (1980), and Miller (1983). Radioactive tracing can be quantitative, but interpretation must be made carefully due to differential mixing, macropore flow, dilution, and non-laminar flow. Some radioactive tracers can add significant information to a hydrologic study. As an example, since tritiated water is very similar to natural groundwater, identical flow pathways and processes can be traced.

Chloride tracers have been used successfully in hydrological tracing studies. Quisenberry and Philips (1976), and McCarty and Walters (1982) both successfully

used chloride to study flow pathways. However, chloride use can be limited in soils with high soluble salt levels due to complexing of ionic pairs and chemical precipitation reactions.

Since Pilgrim and Huff's study has several relevant implications, a detailed description of their study will be given below.

Pilgrim and Huff (1978), on a 30% uniform slope of silty loam, underlain by clay, clay loam, and weathered sandstone, studied surface and subsurface runoff. On a 50 m long by 18 m wide slope, an array of 14 access tubes was staggered on either side of a center line. Cr^{51} and Br^{82} EDTA chelates were distributed along a 12 m injection line. Water was applied by eight sprinklers at a rate of 10.7 mm/hr and after 145 mm of water had been applied, the tracers were injected, and 33 mm more water was applied. This intensity was typical of runoff-producing storms expected at the site. Measurements of tracers began one hour after injection and continued for a 29 hour period. Measurements were then taken daily for three days, and finally at 23 days. Readings were taken at 15 cm vertical intervals by scintillation counter. Two to four days after injection, a hand auger was used to take cores from the four sites.

Significant movement of the tracer occurred for about 24 hours after injection, and small movements were detected for the next 24 hours. There were no further movements

detected after this time. Appreciable activities were measured as far as 30 m downslope and highest activities occurred within 12 m of the injection line. They found that the tracer pattern of distribution was closely related to surface horizon thickness, vegetation condition, and soil moisture content. The authors concluded that tracers provide an excellent potential, especially combined with additional field testing, to increase understanding of processes that are occurring under field conditions.

Lignon et al. (1980), using I^{131} and HOH^{3} tracers on a grassed, 10% slope, in a moisture redistribution study, found a differential rate of water movement through the B horizon. They found that the B horizon, with higher clay content, caused a temporary retention of water, as indicated by activity coefficients.

Both of these last two studies indicated that an impermeable or flow impeding layer can exist in the profile, and that tracers are useful in indicating such flow-impeding zones. However, most tracer studies are only qualitative, rather than quantitative. Pilgrim and Huff (1978) noted that diffusion, miscible displacement, and mixing make the interpretation of tracer studies very difficult for quantitative evaluation, but that they are very useful for qualitative work, and most useful when coupled with other field evaluations.

McCarty and Walter (1982) showed the interactive nature of flow processes. They studied lateral flow on an 8.5%

slope, with a fragipan located 30-45 cm below the surface. Using irrigation, drainage tiles, and flumes, they sampled a saturated profile for up to 120 hours, at depths of 5, 15, and 25 cm. From application and measurement of a known volume and concentration of chloride, flow rates through the soil were calculated. However, using Darcian flow parameters, they calculated a depth of 6 metres necessary to transmit the water flow, although the soil depth was only 30-45 cm. They found that substantial mixing of the surface water must have been occurring with subsurface water. Calculated rates were usually half of the measured rates, and flow was different than anticipated, not as a wetting front or as simple displacement. They concluded that water does not flow over the surface only, but progresses downslope in an irregular flow path, moving vertically up and down on a scale of once per meter. Thus water movement was an interaction among processes, rather than by a single flow process.

C. STATISTICS AND SAMPLING

Introduction

As it is not possible to observe all conceivable events, and since variation exists among all events that are observed, chance is involved in observations and measurements. Chance events will cause uncertainty, but by applying the laws of chance, it is possible to place a

precise and objective measure on uncertainty of inferences (Steel and Torrie, 1980). Thus through a process of inference, particular events can be reasoned to wider generalities.

When data are gathered about certain characteristics, the common trait is variability. Characteristics or observations are usually not specific or constant, but will vary from individual to individual; thus they serve to both group and distinguish various individuals and characteristics that show variation. These observations are called variables - either chance or random variables.

After a body of data has been gathered, one must be concerned whether the data comprises all the possible data or just part of a larger body. A population is all possible values of a variable, while a sample is part of a population. Samples information is used to make an inference about a population.

In scientific experiments it is particularly important to define the population in discussion, and to obtain a representative sample from the population defined - if the sample is to lead to valid inferences. To obtain a valid sample, one needs to apply the rules of randomness to ensure that individual biases do not influence the selection of sample observations. If a sample is truly random, then laws of probability apply and can be used in drawing inferences.

Steel and Torrie (1980) stated that a random sample cannot be drawn without the use of a mechanical process.

Therefore in experimental work, there is a valid reason for restricting randomness, primarily because data are collected with energy expense, time, and effort.

In statistics a common linear additive model is an observation consisting of a mean plus an error. The minimum assumption is that the errors are random, i.e. the mean has been sampled at random. Therefore the observations are probabilistic, rather than deterministic, and a random sample mean is a good estimate of the population mean, since the random sample mean should be close to the population mean, if the sample is large enough. Eventually, through the use of random sampling techniques, a population of sample means is developed, and a derived population from a derived distribution is realized, since it was developed by sampling a parent distribution (Steel and Torrie, 1980). In science, one is usually working with derived populations and distributions, because heterogeneity and physical size precludes sampling the entire population.

Statistics deals largely with drawing inferences about the population parameter; uncertain inferences since they are based on sample evidence for a heterogeneous and large body of soil. Thus in field situations, the experimenter does not know the mean of the population being sampled, but by choosing a certain sample size, a predetermined level of measurement is possible. Then, with a degree of confidence being associated with the estimate of the mean, certain inferences about the data can be made.

Coelho (1974) used the calculation: $N = t^2\sigma^2/D^2$, where N is the number of samples, t^2 is the student' t with (n-1) degrees of freedom at the probability level α, σ^2 is the total variance of the parameter within the field, and D is the specified limit, to calculate the number of samples required to measure six parameters to a known confidence. Estimating the mean within 10% at the 0.05 level of significance for six parameters at five depths from a Pima clay, he determined the number of samples that were required (Table 1).

Statistical methods are commonly used to describe the spatial variability of measured soil physical properties. Recent efforts to characterize the spatial variability of soil properties has centered around determining the frequency distribution of the measurement.

Sampling and normality

A departure from normality can be caused by two main occurrences:

1. if the variability has a finite range, and
2. if the variables are discrete or discontinuous (Steel and Torrie, 1980).

If these departures are small in comparison with the sampling variation, there will be little effect upon inference based on samples.

Theory states:

1. The derived distribution of sample means of random

Table 1. Approximate number of samples required to estimate mean values within 10% at 0.05 significance level for Pima clay (Coelho, 1974).

Parameter	Soil Depth (cm)				
	30	60	90	120	150
15 bars	31	47	62	65	96
% sand	102	149	110	61	29
% silt	22	16	54	104	113
% clay	16	50	64	86	119
Bulk Den.	5	6	5	3	2
Ksat	1011	649	296	903	1439

observations from a normal distribution is also normal.

2. Even if the parent distribution is considered anormal, the distribution of the means of random samples approaches the normal distribution as the sample size increases. This is very important because the form of the parent distribution is rarely known.
3. The sample mean is said to be unbiased because the mean of all possible sample means is the parent population mean (Steel and Torrie, 1980).

Soil properties such as bulk density, organic matter content, clay content, and soil water content at a given tension, are generally characterized by normal distributions, while flow related soil properties such as air permeability, saturated hydraulic conductivity, soil water flux, pore water velocity, and solute dispersion coefficient have been reported to be log-normally distributed (Rao et al., 1979).

Normal and log-normal distributions appear to be the most frequently observed statistical distributions for describing spatial variability of soil physical properties (Rao et al., 1979). Skewness is the most frequent departure from normality (Beckett and Webster, 1971), and generally CV values greater than 100% may be symptomatic of skewed distributions.

Coefficient of variation (CV) has been used as a quantitative index to describe the variability of measured soil physical properties. Although CV describes spatial

variability, Rao et al. (1979) found that the CV does not necessarily provide a good insight into the nature of the statistical distribution of the measurements. The correct specification of the spatial distribution is of primary importance, because the statistical technique used to analyze the measured data depends upon the nature of the distribution. For example, the mean value of normally distributed measurements equals the mode, but for log-normal distribution measurements, the mean may be larger than the mode (Rao et al., 1979). Rao et al. (1979) found that the required sampling size increased with decreasing CV, since the values of coefficients of kurtosis and skewness also decrease with decreasing CV, making it difficult to distinguish between normal and log-normal distributions, thus necessitating a larger sample. They showed that normal and log-normal distributions may adequately describe a set of measurements with CV values equal to or less than 0.4. In such cases accepting the normal distribution, when in fact the true distribution is log-normal, would involve a maximum error of 6-20%, when the mean is used instead of the mode (Rao et al., 1979).

By utilization of consistent random sampling techniques, objective inferences and estimates about the parent population can accurately be made, within a specified degree of confidence, because of the orderly utilization and the universality of the laws of chance, randomness, probability, and normality.

Soil variability

Measurement of the variability of soil physical properties has been identified as being very important in soil hydrologic studies. Beckett and Webster (1971) stated that the proper study of soil variability requires the collection and analysis of a very large number of soil samples, chosen on a probability basis. They state the work is laborious and not glorious, but very necessary. Ball and Williams (1971) stated that with soil heterogeneity, because large variability exists, it is impossible to know what accuracy can be assumed for data derived from a single sample of soil. They concluded that the knowledge of the range of variation is as important as the mean in the interpretation of the analysis. They stress that while knowledge of the mean is important, and does increase with the number of samples taken, the range is just as important and significant in pedological and ecological studies as the mean. Therefore, they stress that as far as is practical, a sampling and analysis program designed for soil property analysis should enable both the mean and the range to be estimated.

In general the range of variation about the mean can be predicted with some accuracy from a system of replicate sampling, and is an important measure. Work involving interpretation of site comparisons, even when an apparently uniform soil is present, must preferably measure either the range of variation, or at least accept the probability that

the quantity measured will have similar CVs to those given in other studies (Ball and Williams, 1971).

Ball and Williams (1971) made assessments of the mean and range of variation of selected soil properties in the surface horizon of a uniform, uncultivated soil by nine sampling programs. Using the most complete sampling program as the standard, (272 samples of 10 cores), they compared the efficiency of the other sampling programs. They found that, in relation to the 66 man day, 275 sample standard, sampling programs using six sample measures and 1.5 man days, made the most reasonable assessment of the mean and the range for most properties and measured more than 50% of the range about a determined mean; while 25-27 samples and six man-days measured at least 2/3 to 3/4 of the total range. Properties measured included: pH, organic matter, and six nutrients. In conclusion, they stated that given that a site permits the alternative possibilities, it is preferable to take the same number of samples in smaller sample plots, whether these are in continuous, regular, or scattered arrangement, rather than to use larger plots.

Beckett and Webster (1971) reviewed a large amount of literature on soil variability, and concluded:

1. soil property variances and CVs increase with the size of the area sampled,
2. up to half the variance within a field may already be present within any 1.0 m^2 in it, and
3. within field variance often changes little with the size

of the field.

They rationalized these statements by using a Continental-Regional-Local argument. They stated the effects of parent material deposition, climate, topography, physical and chemical processes, combined with biological activities, become superimposed on soil. Processes that give rise to soil differences over very short distances introduce variability within all sampling areas, almost regardless of size. Alternately, long range gradations or soil changes caused by the processes of spasmodic or sparse operation will, on the average, make noticeable contributions only to the variability of larger sampling units. So overall the variability of the soil within an area depends very much on the environment, but is likely to increase with the size of the area sampled (Beckett and Webster, 1971). They also stated that in a cultivated landscape there are additional sources of variability in soil subject to human management. Fertilizer placement, growth of crops and residue incorporation superimpose additional heterogeneity on soil chemical properties; while plowing, subsoiling, cultivation, or drainage introduce variations in texture and moisture regime properties. In general, once the sample area exceeds one quarter of the average field area, the average variance for a given property is affected by contributions from between field variance. For soil properties that are greatly affected by management, the between field component of variance tends to be greater than that of more durable

properties.

Webster (1966) found that within areas of 1 m^2, the CV for field moisture content was the lowest in freely drained soils (3-10%), and higher in soils with seasonally high water tables (4-17%), or in fine textured soils with impeded drainage. On a clay loam soil with impeded drainage, CVs within areas of 10 m^2 are 11-26% and vary with season.

Beckett and Webster (1971) stated that soil properties varied with depth, because different soil treatments affect the soil to different depths, and nutrient uptake or water uptake is not always from the same depth as each other, or in different soils. So soil variability is not the same at all depths, nor does it change with depths in the same way for all seasons or for all properties.

III. MATERIALS AND METHODS

A. SITES

Two study sites were established in the Peace River region in 1983, near La Glace and Berwyn, approximately 500 km northwest of Edmonton. These two study sites were located at two runoff-erosion sites established in May 1981 by Chanasyk (described by Chanasyk and Woytowich, 1983). The La Glace site was established on a 5%, west facing slope, 1.5 km east and 1 km north of La Glace. The Berwyn site was located on a 2%, south facing slope, 2 km west and 10 km south of Berwyn.

Five soil runoff-erosion plots were established at the La Glace site and four at the Berwyn site. All runoff-erosion plots were 5 m wide and 75 m long, except runoff-erosion plot #1 at La Glace which was 100 m long. At each site, one runoff-erosion plot was seeded to fescue, while the remaining runoff-erosion plots were in a fallow-canola-barley rotation (Chanasyk and Woytowich, 1983).

These sites were selected for uniformity of slope, as well as site and soil characteristics that were thought to be representative of large areas of the Peace River region.

B. PLOTS

Plots, as utilized in this study, are illustrated in Figure 6. Each plot consisted of four randomly selected sample areas, each located seven meters apart, in a downslope position. Each individual plot was replicated by being divided in half, with two identical treatments applied to each half of the plot. Each replicate or half plot was composed of two sample areas, and at each sample area a 60 cm diameter by 25 cm high steel infiltration ring was driven 5 cm into the soil.

The plots used in this study were situated as follows: at La Glace, the summerfallow plot was located 30 m above the runoff-erosion plots, while at Berwyn, the original runoff-erosion fescue plot was divided into two complete plots, fescue1 and fescue2; while the canola plot was located diagonally 20 m south-east of the runoff-erosion plots. The remaining plots utilized are illustrated in Figure 6 and were superimposed onto the original runoff-erosion plots. Reasons for specific choices of plot locations included limit of accessibility of test equipment, plot design requirements, soil slope uniformity, runoff-erosion plot constraints, and previous test and results comparisons.

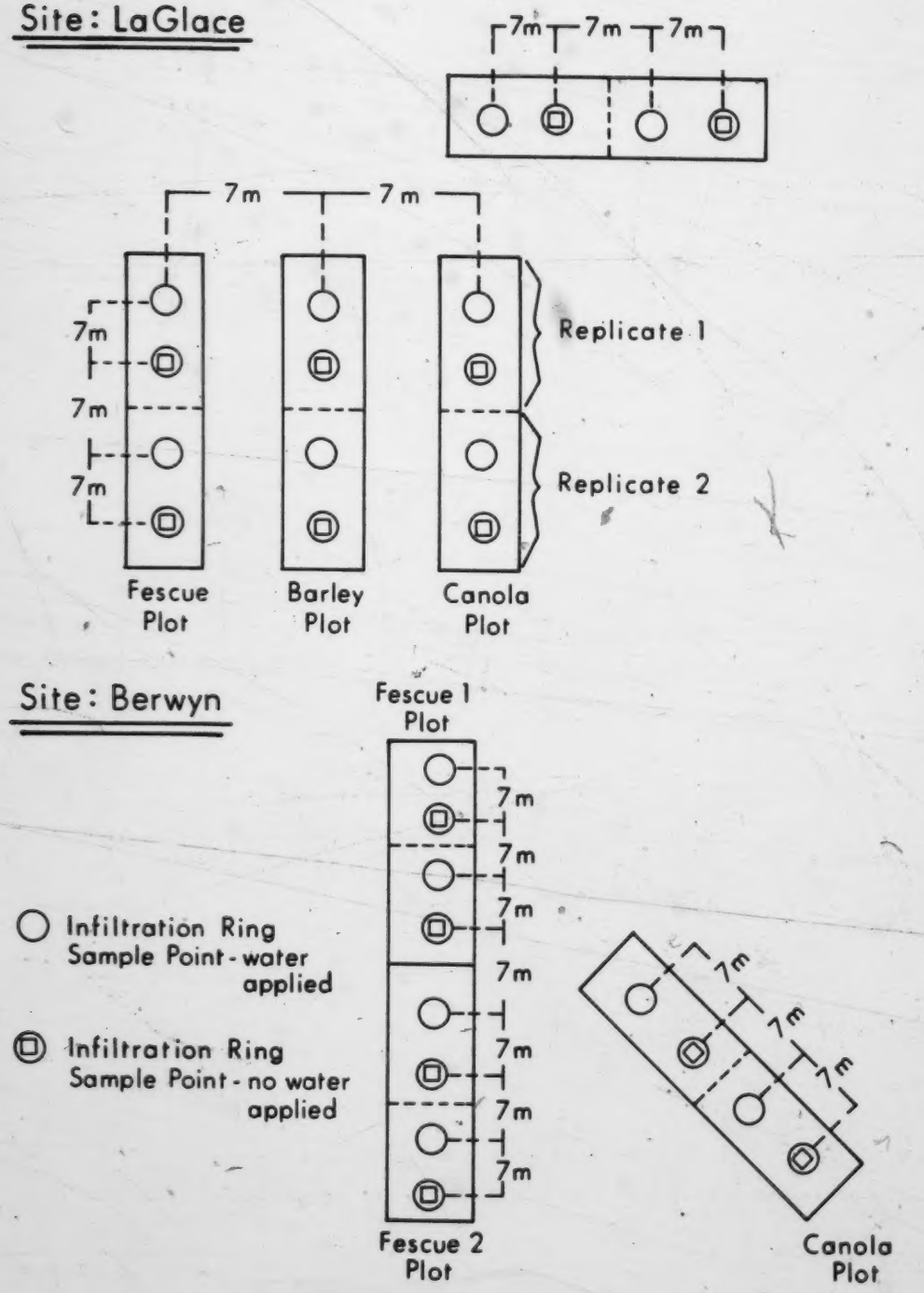


Figure 6. Experimental plot design.

C. INFILTRATION

Ninety litres of water were applied and allowed to infiltrate at one of the two rings in each replicate. Water was continuously monitored for 30 hours during infiltration, with the head maintained above five cm to a maximum of 15 cm. The volume of water to be used was determined by preliminary infiltration trial runs at each site.

In general, after 30 hours of infiltration, all the water had infiltrated the soil, or a constant rate had been reached. Soil sampling was then initiated.

Water was applied only in the second ring of each replicate. Therefore each replicate had two treatments, one to which water was applied (hereafter called 'wet' ring), and the second treatment which did not have any water applied (called the 'dry' ring). Water movement analysis compared the 'wet' ring values against the standard, the 'dry' ring.

D. SAMPLE GRID

Both infiltration rings in each replicate were sampled using a specified sampling overlay (hereafter referred to simply as the 'grid'). The grid is represented in three dimensions in Figure 7. The sample grid overlay was of a four factor randomized block factorial design, which allowed the evaluation of moisture, direction, depth, and distance

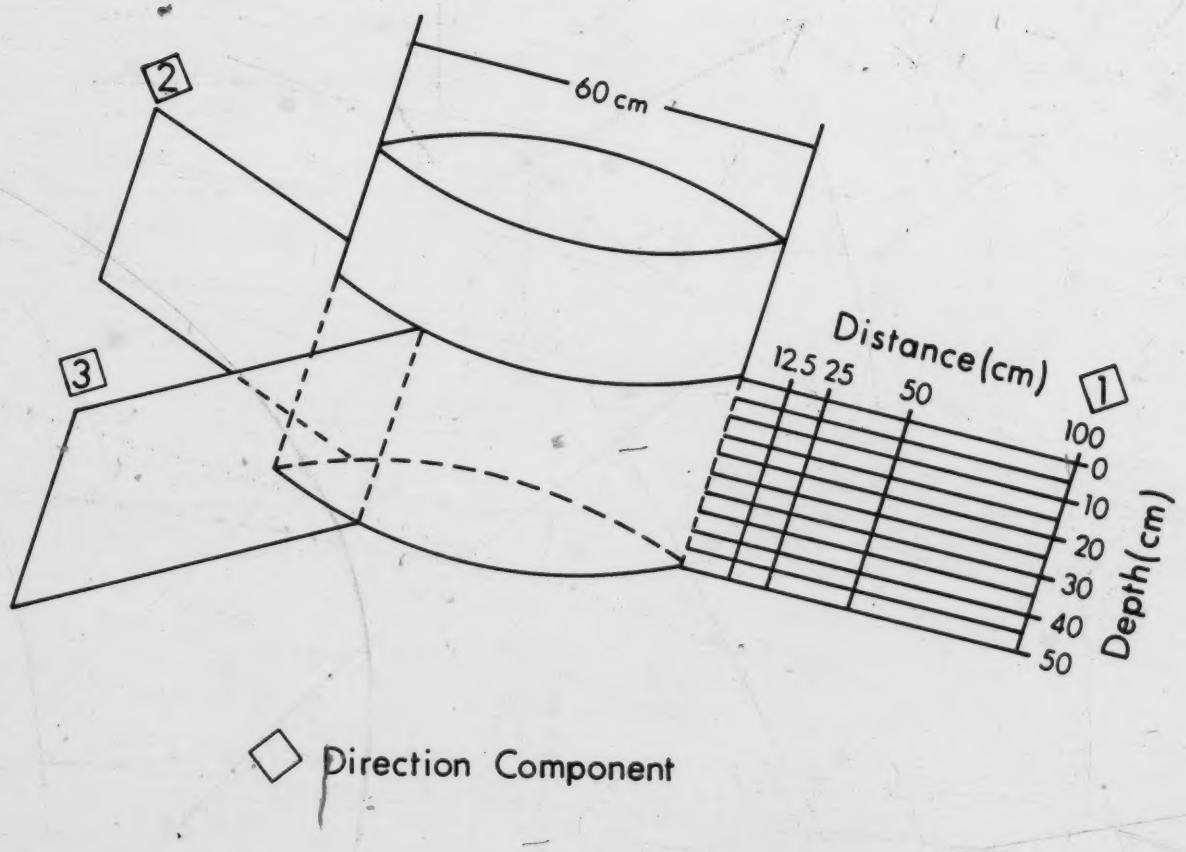


Figure 7. Three dimensional coordinate axis stratified sample grid overlay.

flow components.

The sample grid had three radial arms, each 120° apart. These three arms were consistently numbered from the upslope position in a counterclockwise direction. The arms were numbered one (12 o'clock position), two (eight o'clock position), and three (four o'clock position). The distance component was measured from the outer edge of the infiltration ring, at distances of 12.5, 25, 50, and 100 cm along each of the three arms. At each intersection point of distance and direction, 10 depth increments were sampled, each five cm long to a total depth of 50 cm. Thus on each sample grid, 120 sample increments (10 depths x 4 distances x 3 directions) were identified, each representing a fixed point on a co-ordinate axis, having a depth, direction, and distance component.

E. SOIL SAMPLING

Soil was sampled at each appropriate point and time, using a 2.2 cm diameter Oakfield sampler. At each depth-distance intersection point, 10 successive five cm long soil samples were taken with this sampler. Each sample was individually sealed in a plastic bag and identified. From the center of every infiltration ring, three cores were taken after the soil had dried, using a truck-mounted hydraulically driven 41 mmm diameter core tube. These cores were taken to a depth of 75 cm, divided into 5 cm long

increments, individually sealed in plastic bags, and identified.

F. SOIL CONDITIONS

Since this study was conducted at an existing site, there were a variety of management practices established. At La Glace, the practices were fallow, fescue, canola, and barley, while at Berwyn they were canola and two of fescue (called fescue1 and fescue2). The appropriate management practice designation was retained for identification purposes only, as a vegetation variable parameter was not included in the experimental analysis or objectives.

G. SOIL PHYSICAL PROPERTY STUDY

Selected soil physical properties important to flow component evaluation and to the characterization of variability were determined by the following analyses:

Bulk Density

Samples used for the determination of bulk density were taken by hydraulic core after the soil had dried from the infiltration tests. Three 41 mm by 5 cm diameter cores were taken from within each infiltration ring. These soil samples were dried at 105°C for 24 hours and weighed. Corrections made to the original mass and volume were made by separating

coarse particles with a 2 mm sieve, then determining the stone mass and volume, and subtracting the appropriate value from the original measurement.

Texture

Particle size was determined using the hydrometer method (Day, 1965). All particle size distributions were based on the CSSS soil separates classification scale, according to the method of McKeague (1978). Using the soil samples taken by hydraulic core, 40 g oven dry samples were dispersed in 100 ml sodium hexametaphosphate, the volume brought up to 1 litre with distilled water, and left to equilibrate for at least 12 hours. Organic matter and foam were dispersed using a few drops of amyl alcohol. The actual percentage of the respective fractions was calculated by interpolating within the four time intervals. Time intervals used were: 30 seconds and one minute for sand, and nine hours and 12 hours for clay. Silt was calculated by difference. All temperature corrections and calculations were according to McKeague (1978).

Available Water Holding Capacity (AWHC)

Available water holding capacities were determined for the samples taken with the hydraulic core, using the pressure plate apparatus as described by Richards (1954). Moisture retention was determined at -33 kPa and -1500 kPa. The difference between these two values was the available

water holding capacity (AWHC). All samples were run for 48 hours; a standard sample was included with each run.

Field Moisture Contents

Field moisture contents were determined from grid samples taken with the Oakfield sampler. These 2.2 cm diameter by 5 cm long samples were weighed, oven dried at 105°C for 24 hours and reweighed. Moisture contents were determined on a mass basis.

Site Sampling Scale

There were two sampling scales used in this study. A small scale, approximately six square meters, and referred to as the grid scale, was used at each site. For this scale sampling was facilitated using the grid overlay shown in Figure 7. All soil physical properties just discussed were determined for this scale.

A larger scale of sampling, referred to as the field scale, was also used at each site. The field scale was a composite of all sample grids used on the study site. The area involved in the sample site was 500 m^2 at Berwyn and 1800 m^2 at La Glace, shown in Figure 6.

The two different sampling scales were used to provide information on spatial and temporal variability, and on field heterogeneity. Also the two scales permitted evaluation of estimates of the means and the number of samples required to achieve a known precision.

H. WATER STATUS STUDY

To determine the variability of soil water characteristics and to evaluate the change in soil water status with location on a coordinate axis grid after application of a known amount of water, a water status study was completed. Using the field moisture contents, the four factor randomized block factorial design of the grid, and the replicated plot designs, the presence of a subsurface lateral flow component was evaluated statistically. Using the University of Alberta's Amdahl 5860 computer and the APL statistical package "Statpack3 Sec5" ANOVA's were performed on the plot data using a linear model (Table 2). The null hypothesis evaluated was Ho: soil water status is not a function of location on a coordinate axis grid. If the Ho hypothesis was rejected, then soil water status was a function of location, and if so, water preferentially moved within the soil profile during the water infiltration process. If the null hypothesis was rejected, then water did move laterally, and the presence of this subsurface lateral flow component could be verified statistically.

If the presence of a subsurface lateral flow component was statistically verified, the final step of the water analysis study was to evaluate the extent of the component. Again, using the plot field moisture content data and the ANOVA analysis, significantly or highly significantly (95% or 99%, respectively) different moisture results were tested

Table 2. Factorial design.

Linear Model

$$Y = M + A + B + C + D + BC + BD + CD + BCD + E$$

Factor	Levels
Block	2
Moisture	2
Direction	3
Distance	4
Depth	10

ANOVA

	Source of Variation	Degrees of Freedom
A	BLOCKS (2 reps)	1
B	MOISTURE (wet or dry)	1
C	DIRECTION (3 rays)	2
D	DISTANCE (3 or 4)	3
BC	Moisture x Direction	2
BD	Moisture x Distance	3
CD	Direction x Distance	6
BCD	Moisture x Distance x Direction	6
E	Error	23
	TOTAL	47

using Duncan's New Multiple Range (NMR) Test. (Standard 'dry' grid moisture content versus infiltrated 'wet' moisture content, in the same plot).

Each of the ten depth increments for the plot was individually evaluated for comparative moisture content differences between wet and dry grids. If the result was significant, then the actual lateral flow component was calculated for each depth increment as the % of the total water volume added. These individual lateral flow components were added together as a total cumulative lateral flow component % for the entire plot. Thus, the subsurface lateral flow component that was statistically confirmed was quantitatively evaluated as well.

IV. RESULTS AND DISCUSSION

A. SOIL PHYSICAL PROPERTY STUDY

The soil physical property variables that were determined are summarized in Tables 3A, 3B, 5A, 5B, and 7, with the coefficients of variation (CVs) of these variables summarized in Tables 4A, 4B, 6A, 6B, 8A, and 8B. A summary of the ranges, minimum and maximum values and averages of both the values and CVs is presented in Table 7. Table 8A contains calculations of mean CVs of all variables by depth, while Table 8B summarizes CVs of all variables into two groups: 0-25 cm and 25-50 cm. All tables include both small and large scale determinations for all properties and variability studied. Each property at each site is individually discussed below.

FIELD MOISTURE CONTENT

La Glace

Field moisture content generally increased from a low at the surface to a maximum value, then decreased with increasing depth for both grid and field means (Tables 5A and 5B). (Field moisture content refers to an average of grid samples taken from 'dry' rings from each replicate). For the grid means (Table 5A), the 30-35 cm depth had the

Table 3A. Berwyn grid means.

Depth cm	Field Moisture Content %*	-33 kPa %*	-1500 kPa %*	AWHC %*	Texture S %	Texture Si %	Texture C %	DB Mg m^{-3}
0-5	29.4	33.5	16.1	17.4	26	57	17	0.82
5-10	27.9	33.8	15.9	17.9	26	58	16	0.97
10-15	19.0	33.2	15.7	17.5	25	59	16	1.17
15-20	11.0	26.3	10.0	16.3	24	57	19	1.36
20-25	11.0	23.1	10.9	12.2	23	46	31	1.44
25-30	15.7	26.0	15.0	11.0	18	39	43	1.43
30-35	16.2	27.4	17.0	10.4	17	33	50	1.47
35-40	15.9	29.1	17.5	11.6	16	33	51	1.51
40-45	15.7	28.7	16.8	11.9	16	33	51	1.51
45-50	15.5	27.7	16.0	11.7	17	34	49	1.46

* Mass Basis

Table 3B. Berwyn field means.

Depth cm	Field Moisture Content %*	-33 kPa %*	-1500 kPa %*	AWHC %*	Texture S %	Texture Si %	Texture C %	DB Mg m^{-3}
0-5	26.5	31.2	13.5	17.7	28	57	15	0.90
5-10	24.7	29.0	12.8	16.2	30	54	16	1.06
10-15	16.5	25.0	10.8	14.2	30	49	21	1.23
15-20	10.9	22.2	10.7	11.5	28	44	28	1.32
20-25	12.6	23.3	13.2	10.1	24	38	38	1.31
25-30	15.9	24.8	15.2	09.6	20	35	45	1.47
30-35	16.2	25.9	15.7	10.2	19	34	47	1.50
35-40	15.9	26.0	15.8	10.2	19	34	47	1.52
40-45	15.5	26.2	15.8	10.4	19	35	46	1.57
45-50	15.4	26.0	15.5	10.5	19	35	46	1.61

* Mass Basis

Table 4A. CVs for Berwyn grid means.

Depth	Field Moisture Content	-33 kPa	-1500 kPa	AWHC	Texture S	Texture Si	Texture C	DB
cm	%	%	%	%	%	%	%	Mg m^{-3}
0-5	6	4	5	9	4	3	5	15
5-10	5	2	8	10	9	1	7	11
10-15	6	5	7	8	2	0	3	18
15-20	22	9	19	4	10	2	17	10
20-25	30	7	13	11	13	11	21	2
25-30	13	5	6	10	7	13	15	4
30-35	7	3	3	10	6	4	3	1
35-40	7	3	6	3	9	5	2	7
40-45	6	1	5	6	4	8	5	5
45-50	5	2	4	9	6	5	5	7
Mean	11	4	8	9	7	5	8	7

Table 4B. CVs for Berwyn field means.

Depth	Field Moisture Content	-33 kPa	-1500 kPa	AWHC	Texture S	Texture Si	Texture C	DB
cm	%	%	%	%	%	%	%	Mg m^{-3}
0-5	11	11	16	19	33	7	8	14
5-10	4	13	15	25	14	8	26	10
10-15	10	18	22	29	18	14	39	11
15-20	20	14	34	35	29	21	47	6
20-25	8	10	21	24	19	16	24	6
25-30	6	9	14	17	16	8	13	4
30-35	14	9	12	19	13	7	10	5
35-40	5	7	8	17	13	8	10	5
40-45	5	7	7	14	9	10	10	3
45-50	8	5	7	13	12	10	11	4
Mean	9	10	16	21	18	11	20	7

Table 5A. La Glace grid means.

Depth cm	Field Moisture Content %*	-33 kPa %*	-1500 kPa %*	AWHC %*	Texture S %	Texture Si %	Texture C %	DB Mg m^{-3}
0-5	16.4	30.2	14.3	15.9	25	46	29	1.04
5-10	17.9	30.8	15.1	15.7	24	46	30	1.04
10-15	17.3	29.5	13.5	16.0	27	46	27	1.14
15-20	16.0	26.4	13.1	13.3	25	[illegible]	36	1.26
20-25	18.4	28.3	15.2	13.1	20	35	45	1.41
25-30	20.9	30.2	17.1	13.1	20	31	49	1.45
30-35	21.7	30.4	18.0	12.4	22	25	53	1.42
35-40	21.0	30.4	17.7	12.7	22	26	52	1.53
40-45	19.4	30.2	17.5	12.7	21	26	53	1.55
45-50	18.1	29.9	16.9	13.0	23	26	51	1.55

* Mass Basis

Table 5B. La Glace field means.

Depth cm	Field Moisture Content %*	-33 kPa %*	-1500 kPa %*	AWHC %*	Texture S %	Texture Si %	Texture C %	DB Mg m^{-3}
0-5	17.3	30.2	16.1	14.1	24	45	31	1.00
5-10	18.9	30.1	16.2	13.9	23	45	32	1.12
10-15	19.4	29.5	17.2	12.3	20	41	39	1.24
15-20	20.5	29.9	18.1	11.8	19	35	46	1.29
20-25	23.0	31.2	19.4	11.8	17	28	55	1.36
25-30	24.4	31.9	19.6	12.3	16	26	58	1.40
30-35	24.3	32.2	20.0	12.2	17	24	59	1.45
35-40	23.3	31.4	19.3	12.1	17	26	57	1.51
40-45	22.2	29.9	17.8	12.1	18	28	54	1.56
45-50	21.4	29.6	17.2	12.4	19	30	51	1.61

* Mass Basis

Table 6A. CVs for La Glace grid means.

Depth	Field Moisture Content	-33 kPa	-1500 kPa	AWHC	Texture S	Texture Si	Texture C	DB
cm	%	%	%	%	%	%	%	Mg m^{-3}
0-5	8	3	2	6	7	1	4	6
5-10	7	3	3	7	6	3	2	6
10-15	13	4	10	7	4	2	6	10
15-20	15	3	9	12	7	12	11	7
20-25	24	6	13	11	6	14	12	6
25-30	14	4	7	10	18	13	12	2
30-35	7	5	5	6	24	7	9	6
35-40	9	5	8	5	22	8	11	5
40-45	9	3	8	5	18	6	10	8
45-50	8	4	5	3	8	18	9	6
Mean	11	4	7	7	12	8	9	6

Table 6B. CVs for La Glace field means.

Depth	Field Moisture Content	-33 kPa	-1500 kPa	AWHC	Texture S	Texture Si	Texture C	DB
cm	%	%	%	%	%	%	%	Mg m^{-3}
0-5	11	6	8	19	4	3	6	6
5-10	7	6	8	20	8	5	11	8
10-15	16	5	15	16	21	18	27	11
15-20	21	11	16	15	28	23	26	8
20-25	16	12	13	17	27	21	17	8
25-30	12	11	13	18	30	20	15	6
30-35	13	10	9	16	25	13	11	4
35-40	17	9	9	14	22	13	10	5
40-45	19	11	12	17	28	16	14	3
45-50	19	10	13	15	30	13	16	4
Mean	15	9	12	17	22	15	15	6

Table 7. Variations in values and CVs for 10 depths.

	La Glace		Berwyn	
	Grid Means	Field Means	Grid Means	Field Means
	(% by mass)			
Field Moisture Content				
% (Min-Max)	16.0-21.7	17.3-24.4	11.0-29.4	10.9-26.5
Range %	5.7	7.1	18.5	15.6
CV	8-24	7-21	5-30	4-20
Range %	5.7	7.1	18.5	15.6
Range (CV)	16	14	25	16
Ave. CV	11	15	11	9
-33 kPa				
% (Min-Max)	28.3-30.8	29.5-32.2	23.1-33.8	22.2-31.2
Range %	2.5	2.7	10.7	9.0
CV	3-5	5-12	1-9	5-18
Range (CV)	2	7	8	13
Ave CV	4	9	4	10
-1500 kPa				
% (Min-Max)	13.1-18.0	16.1-20.0	10.0-17.5	10.7-15.8
Range %	4.9	3.9	7.4	5.1
CV	2-13	8-16	3-19	7-34
Range (CV)	11	8	16	27
Ave CV	7	12	8	16
AWHC				
% (Min-Max)	12.4-16.1	11.8-14.4	10.4-17.9	9.6-17.7
Range %	3.6	2.6	7.5	8.1
CV	3-12	14-20	4-13	13-35
Range (CV)	9	6	9	22
Ave CV	7	17	9	21

Table 7. Variations in values and CVs for 10 depths (cont'd).

Texture	La Glace		Berwyn	
	Grid Means	Field Means	Grid Means	Field Means
Sand (Min-Max)	19.8-25.2	16.3-23.5	15.5-26.2	18.8-30.1
Silt (Min-Max)	25.1-46.4	24.6-45.9	33.2-59.5	33.9-54.0
Clay (Min-Max)	27.2-53.1	30.7-58.7	15.5-51.3	15.2-47.0
Sand				
% (Min-Max)	19.8-25.2	16.3-23.5	15.5-26.2	18.8-30.1
Range %	5.4	7.2	10.7	11.3
CV	4-24	4-30	2-13	9-33
Range (CV)	20	26	11	24
Ave CV	12	22	7	18
Silt				
% (Min-Max)	25.1-46.4	24.6-45.9	33.2-59.5	33.9-54.0
Range %	21.3	21.3	26.3	20.1
CV	1-18	3-23	0-13	7-21
Range (CV)	17	20	13	14
Ave CV	8	15	5	11
Clay				
% (Min-Max)	27.2-53.1	30.7-58.7	15.5-51.3	15.2-47.0
Range %	25.9	28.0	10.7	11.3
CV	2-12	6-27	2-21	8-47
Range (CV)	10	19	19	39
Ave CV	9	15	8	20
Bulk Density				
(Min-Max)	1.04-1.55	1.00-1.61	.82-1.46	.90-1.61
Range (g/cm^3)	0.51	0.61	0.64	0.71
CV	2-10	3-11	1-8	3-14
Range (CV)	8	8	7	11
Ave CV	6	6	7	7

Table 8A. CV mean differences between depths for all properties.

	La Glace CVs				Berwyn CVs			
Depth	Grid Means		Field Means		Grid Means		Field Means	
0-5	4.6		7.9		5.6		14.9	
change		-0		+1.2		+1.0		-0.5
5-10	4.6		9.1		6.6		14.4	
change		+2.4		+7.0*		-0.4		+5.7
10-15	7.0		16.1		6.2		20.1	
change		+2.5*		+2.4		+5.4*		+5.7
15-20	9.5		18.5		11.6		25.8	
change		+2.0		-2.1		+1.9		-9.8*
20-25	11.5		16.4		13.5		16.0	
change		-1.5		-0.8		-4.4		-5.1
25-30	10.0		15.6		9.1		10.9	
change		-1.4		-3.0		-4.5		+0.2
30-35	8.6		12.6		4.6		11.1	
change		+0.5		-0.2		+2.0		-2.0
35-40	9.1		12.4		6.5		9.1	
change		+0.7		+2.6		+1.5		-1.0
40-45	8.4		15.0		5.0		8.1	
change		-0.8		-0		-0.4		+0.7
45-50	7.6		15.0		5.4		8.8	

* indicates the largest change

Table 8B. CV mean totals for all properties.

	La Glace CVs		Berwyn CVs	
Depth	Grid Means	Field Means	Grid Means	Field Means
0-25	7.4	13.6	8.7	18.2
25-50	8.7	14.1	6.1	9.6
Ave	8.1	13.9	7.4	13.9

maximum moisture content, while for the field mean (Table 5B) highest moisture contents were at the 25-35 cm depths. At each of these depths, a corresponding maximum also occurred in -33 kPa and -1500 kPa moisture retention values and % clay values. Overall the grid moisture contents had a 5.7% range (Table 7), while the field moisture contents had a slightly higher range (7.1%). These ranges were higher than other property ranges except for silt and clay percentages.

CVs for the grid means (Table 6A) increased to a maximum at the 20-25 cm depth, then decreased with increasing depth. The field mean CVs did not exhibit such a clear pattern (Table 6B) and remained variable through all depths. The range of CVs and average CV values (Table 7) was more variable, relative to the other properties studied, with the exception of texture. The mean CV for the total 10 depths (Table 7) increased as the sample size increased. Guma'a (1978) found that CV values for field moisture content ranged from 21-42.5 % for two depths (30 and 60 cm). Webster (1966) found CV values for field moisture content ranging from 3-10% in well drained soils. Soils at La Glace were both high in clay and imperfectly drained, and values (Tables 6A and 6B) are similar to those reported by Webster.

Berwyn

Field moisture content for the grid means were highest at the surface (Table 3A), decreased to a minimum at the

15-25 cm depth, then remained relatively constant with depth. The field means (Table 3B) exhibited a similar pattern of maximum values at the surface, decreasing to a minimum at the 15-20 cm depth, then remaining constant below this depth. The first two depth increments (Tables 3A and 3B), for both the grid and field means, had maximum -33 kPa moisture retention, AWHC, and % silt, and the lowest bulk density values. Coelho (1974) found that field moisture content at field capacity increased consistently with an increase in silt percentages to all depths for three soils he studied (r values up to 0.7). In both grid and field means at Berwyn, the first three depth increments had the greatest field moisture contents and the greatest silt contents. The range in values for the field moisture content (Table 7) was greater for the grid means (18.5%) than for the field means (15.6%). These ranges were the largest of all properties studied, excluding silt.

CVs for the grid means (Table 4A) were greatest in the 15-30 cm depth interval. Maximum CV occurred for the 15-20 cm interval (Table 4B), for the field means. Moisture CV range (Table 7) and average CV for the total depth were the largest, relative to other properties. Alternately, in the field means, both CV range and average total CV were among the lowest values, relative to other properties. These CV values were similar to those reported by Webster (1966).

WATER RETENTION AT -33 kPA

La Glace

Water retention at -33 kPa (Tables 5A and 5B) was similar at all depths, for both grid and field means. Value ranges across all depths were 2.5% and 2.7% for the grid and field means, respectively (Table 7), the smallest, or near the smallest range for all properties measured.

The CV average for total depth (Tables 6A and 6B) increased as sample size increased from grid to field means (4 to 9, respectively). These CV values were the lowest of those for all properties studied from grid means, and second lowest for field means. The average total depth CV value of 9.0 on a field scale (Table 6B) compares to water retention values reported in the literature of 15.5 by Coelho (1974) at a similar depth, and 20-26 by Guma'a (1978).

Berwyn

Water retention at -33 kPa was maximal at the surface, decreased to a minimum value at depths of 20-25 cm and 15-20 cm, for grid and field means, respectively (Tables 3A and 3B). The value ranges were 10.7% and 9.0% for the grid and field means, respectively (Table 7), were lower than in situ field moisture content and silt, similar to sand and clay, and greater than -1500 kPa for grid and field mean values.

Average depth CVs were lowest for all properties for grid means (Tables 4A, 4B, and 7), while the field means

were third lowest. Increased sampling size resulted in a decrease in range, but a large increase in average CV for all depths (Table 7).

WATER RETENTION AT -1500 kPA

La Glace

The maximum value for both the grid and field means occurred at the 30-35 cm depth, which corresponded to the maximum clay percentage (Table 5A and 5B). The range for water retention at -1500 kPa (Tables 5A, 5B, and 7) was higher than that at -33 kPa, for both grid and field means, but lower than the rest of the properties studied. Range decreased as the number of samples increased from grid to field scale (Table 7).

The average depth CVs for both grid and field means (Tables 6A and 6B) were the third lowest of the properties studied. The CV range decreased as the sample size increased, but average depth CV was larger for the larger sample size (Table 7).

Berwyn

Water retention at -1500 kPa was lowest in the 15-20 cm depth, and maximum at the 35-40 cm depth for both the grid and field scales (Tables 3A and 3B). The maximum -1500 kPa values correspond to the maximum clay percentage values, similar to La Glace (Tables 3A, 3B, 5A, and 5B) and to

Coelho's (1974) results. The -1500 kPa value range at Berwyn was greater than the corresponding range at La Glace (Table 7), but exhibiting similar patterns of value decrease with increased sample size.

The CV range and average depth results (Table 7) tended to be more variable than most other properties; with field moisture content and AWHC higher on a grid scale, and AWHC, and sand and clay being higher on the field scale. CV range and average depth CVs for -1500 kPa increased with increasing sample size. The 15-20 cm depth range, which exhibited the lowest value range also exhibited the greatest variability (Table 3A, 3B, 4A, and 4B) for both the grid and field scale.

AVAILABLE WATER HOLDING CAPACITY (AWHC)

La Glace

Grid and field mean values for AWHC were highest in the first three depth increments, corresponding to maximum silt values (Tables 5A and 5B). Although organic matter content was not determined, it would have also been greatest for these depth increments, as the Ah horizon was a characteristic for all these soils. The range in AWHCs was small relative to other properties studied (Table 7). The CV range was much larger for the grid compared to the field average CV range (Table 7) The grid mean showed a maximum CV variation at the 15-30 cm depth, while the field means did

not show a consistent CV pattern. Also, average CVs for all depths were more variable on a field scale, relative to all other properties studied (Tables 5A and 5B).

Berwyn

Maximum AWHC occurred in the first three depth increments, both on a grid and field scale (Tables 3A and 3B). These depth increments also contained maximum % silt. The soils at Berwyn had a much greater range of AWHC than did those at La Glace (Table 7).

CV variation was greatest at depths of 5-25 cm (Table 4B), on a field scale. CV variation for AWHC was relatively large, compared to all other properties (Tables 4A and 4B). Increasing the sample size from a grid to a field scale resulted in a doubling of the CV range and average value for AWHC measurements (Table 7).

TEXTURE

La Glace

These soils were predominantly silt and clay (Tables 5A and 5B). Range of % sand (5.4%) was lowest of all values for particle size determined, while silt and clay had ranges greater than 20% (Table 7). Again, increasing sampling size from grid to field scale resulted in increased variability, as the CV range and average values increased with the larger scale of sampling (Tables 6A, 6B, and 7).

The sand values were lower than the silt or clay values, but the CV ranges and average depth CVs (Tables 5A, 5B, and 7) were greater than for silt or clay. Generally sand decreased with depth to 30 cm, then increased slightly at greater depths for both the field and grid means (Tables 5A and 5B). Grid CVs were larger for depths greater than 25 cm, compared to depths less than 25 cm, by two to four times (Table 8B). Field CVs were similar from the 10 cm depth down (Tables 5A and 5B).

Silt values were maximum at the surface and decreased with depth, for both grid and field scales (Tables 5A and 5B). Silt values were above 40% in the 0-15 cm depths, then steadily decreased to 25-26% at the 30 cm depth, then slightly increased at greater depths. CV values were the greatest in the 15-30 cm depth for both grid and field scale sample sizes (Tables 6A, 6B, and 8A).

Clay generally increased with depth and reached a maximum value at 30-35 cm (Tables 5A and 5B). Clay had the largest range in values, with a 26-28% range (Table 7). Clay CV range was not as great as was the silt CV range, but was larger than sand (Table 7). CV values for clay grid scale samples were maximum for the depth interval 15-30 cm while the field CV values were maximum at 10-30 cm (Tables 6A and 6B). The average CV with depth was similar to silt, with the average field CV greater than the grid CV (Tables 6A and 6B).

Berwyn

The soil was dominated by clay and silt (Tables 3A and 3B). While sand and clay had similar ranges for both grid and field means, % sand was not greater than 30.1% (Table 7). Silt was predominant in the upper 25 cm for the grid scale means and the upper 20 cm for the field scale means. Clay was the largest textural component below 25 cm for both scale means (Tables 3A and 3B). Increased sampling scale did not result in a large difference in % range, but did result in at least a doubling in the average CV values (Table 7).

The 15-30 cm depth increment for sand, silt, and clay for grid CVs, and the 10-30 cm depth increments for field CVs, were particularly variable, relative to the other depths.

In the grid scale, the proportions of the three textural separates remained the same for the top four depth increments, and again for the bottom four depth increments. The 20-30 cm depth was the zone in which changes in textural separates proportions occurred. In the field sample, the textural separates proportions at the top three depth increments, and then at the bottom five depth increments were relatively similar. The change from a silt- to a clay-dominated profile occurred in the 15-25 cm zone (Tables 3A and 3B).

TEXTURAL COMPARISON OF SITES

The soils at Berwyn were dominated by clay and silt. These soils exhibited a slightly higher % sand and a greater range than did the soils at La Glace, much higher % silt, but with similar range to La Glace, and lower clay contents, with 2.5 to 3 times lower ranges (Tables 3A, 3B, 5A, 5B, and 7). Soils at Berwyn generally had more silt at all depths. In the upper 25 cm the soils at Berwyn had much lower clay contents than did the soils at La Glace (Tables 3A, 3B, 5A, and 5B). Sand % was similar at all depths for both soils.

Generally the CV average means for total depth were similar at both sites, with the grid range CVs being lower for sand and silt, but higher for clay (Tables 4A, 4B, 6A, 6B, and 7). On a field scale, the clay CVs at Berwyn had a greater range than did the clay CVs at La Glace (Table 7). The soils at Berwyn and La Glace do not generally exhibit large differences in variability and several similarities in variability existed. On a grid scale, soils at both La Glace and Berwyn had a zone which seemed to be particularly variable, the 15-30 cm depth. At the field scale, this variable zone was present, but expanded to the 10-30 cm depth. Increased sample scale resulted in increased variability (Tables 4A, 4B, 6A, 6B, and 8A).

BULK DENSITY

La Glace

Bulk density was relatively constant with depth compared to other properties. It increased with depth to a maximum near the 50 cm depth for both grid and field scale samples. The soils exhibited little variability, with the maximum variability at the 10-15 cm depth, for both the grid and field scale (Tables 6A and 6B). Bulk density was the least variable property for the La Glace field scale, and second for the grid scale. The low average bulk density CVs (6%) were similar to those reported by Coelho (1974) for various depths for 180 samples (7 to 12%). Guma'a (1978) analyzing 64 core samples, found that CVs were all less than 8%.

Berwyn

Soils were slightly more variable at the surface, compared to the soils at La Glace. Bulk density increased with depth to the maximum near the 50 cm depth (Tables 3A and 3B). The CV average for all depths (Tables 4A, 4B, and 7) indicated that CV for bulk density was the lowest for all properties studied on a field scale, and the third lowest on the grid scale. The CV range was slightly higher for the field scale relative to the grid scale, but the overall average CV for total depth was the same. The greatest variability was found in the uppermost four depth increments

for both the grid and field scale, with relatively lower values found in depth below this depth (Tables 4A, 4B, and 8A). Coelho (1974) found a close relationship between bulk density and percentage sand and silt, but such a relationship was not noted in this study.

SUMMARY OF PHYSICAL PROPERTIES

La Glace

The soil was characterized by a high percentage of silt and clay (Tables 5A and 5B), with a horizon change at 10-20 cm (Table 8A). This change was confirmed by visual observations. The A horizon was predominately silt (46-34%), while the B horizon had high % clay (45-59%). The top 20 cm also had the highest AWHC and lowest bulk density (Tables 5A and 5B).

Maximum variability, expressed as CV, was found at 10-20 cm, where the soils changed from a silt dominated, high water holding capacity A horizon, to a higher density, clay dominated B horizon (Tables 8A, 4A, and 4B). Overall, the soils exhibited relatively uniform physical property variability at all depths (Table 8B). The properties in general were more variable as the sample area increased (Tables 6A, 6B, and 7A). Soil physical properties ranked in variability as follows (from the lowest CV to the highest CV): Grid (Table 6A): -33 kPa water retention, bulk density, -33 kPa and -1500 kPa water retention, AWHC, % silt, % clay,

field moisture content, and % sand. Field (Table 6B): bulk density, -1500 kPa water retention, % silt, % clay, field moisture content, AWHC, % sand.

Berwyn

The soil had high % silt, low % clay, in the upper 25 cm, with high % clay, higher density soil in the lower 25 cm (Tables 3A and 3B) On both a grid and a field scale, the 10-25 cm depth zone was the more variable, with the upper 25 cm more variable than the lower 25 cm (Tables 4A, 4B, and 8B).

The top 10 cm exhibited low bulk density, and the top 15 cm had the greatest AWHC (Tables 3A and 3B), corresponding to a very high silt percentage. A sharp demarcation in AWHC was found below 20 cm on the grid, and below 15 cm on the field scale. This corresponded to low values of water retention at -1500 kPa and % clay, high CV values in the transition zones and increasing bulk density (Tables 3A, 3B, and 8A).

Soils were more variable on a field scale than on a grid scale (Tables 4A and 4B). The field scale upper 25 cm were highly variable (Table 8A), while the grid scale exhibited slightly more variability in the upper 25 cm relative to the lower 25 cm. The soils were markedly variable in the 15-30 cm depth (Table 8A).

Soil physical properties ranked in variability as follows (from the lowest CV to the highest CV): Grid (Table

4A): -33 kPa moisture retention, % silt, bulk density, % sand, -1500 kPa moisture retention, % clay, AWHC, and field moisture content; Field (Table 4B): bulk density, field moisture content, -33 kPa moisture retention, % silt, -1500 kPa moisture retention, % sand, % clay, and AWHC.

TOTAL FIELD CV

The CVs for all properties studied were added across depth increments to derive a depth total field CV value (Table 8A) as a relative index for three purposes:

1. to distinguish the most variable depths or transitional zones in the profile,
2. to help identify stratified discontinuities in the profile, and
3. to study the variability of the upper 25 cm of the profile relative to the lower 25 cm variability.

1. The Transition Zones (Table 8A).
   La Glace: grid 15-30 cm; field 10-30 cm.
   Berwyn: grid 15-30 cm; field 10-25 cm.
2. The Discontinuities (Table 8A).
   La Glace: grid 10-20 cm; field 5-15 cm.
   Berwyn: grid 10-20 cm; field 15-25 cm.
3. Depth (Table 8B).
   Dividing the profiles by depth showed that the field

means for the upper 25 cm were more variable than the lower 25 cm, with Berwyn slightly more variable than La Glace (18.2% versus 13.6%, respectively). Berwyn was more uniform below 25 cm than above, while at La Glace, the top was slightly more uniform than the bottom. The grid means for both sites were similar when compared to between sites and between depths of the profile.

EFFECT OF SAMPLE SIZE

Two sampling scales were used in the study to evaluate the change in variability with size of sampling area. In designing a sampling program, generally it would be expected that a larger sample size and larger area would provide a more accurate estimate of the mean, and that variability should decrease as the sample size increased. Changes in values and variability with an increase in sample number and area from a grid scale to a field scale are summarized in Table 9.

At Berwyn, only field moisture content precision increased with more samples. For all other properties at Berwyn, while more precise estimates of the mean values may have been determined, variability range and values were all increased. This trend was also found at La Glace, with the exception of an increase in field moisture content values, while variability range and values decreased.

Table 9. Change in value and variation as sample size increased.

Berwyn	Value	CV Variation	
Property	Range	Range	Average Value
Field MC	Decreased	Decreased	Decreased
-33 kPa	Decreased	Increased	Increased
-1500 kPa	Decreased	Increased	Increased
AWHC	Decreased	Increased	Increased
Sand	Increased	Increased	Increased
Silt	Decreased	Increased	Increased
Clay	Increased	Increased	Increased
Bulk Density	Increased	Increased	Same

La Glace	Value	CV Variation	
Property	Range	Range	Average Value
Field MC	Increased	Decreased	Decreased
-33 kPa	Increased	Increased	Increased
-1500 kPa	Decreased	Increased	Increased
AWHC	Decreased	Increased	Increased
Sand	Increased	Increased	Increased
Silt	Same	Increased	Increased
Clay	Increased	Increased	Increased
Bulk Density	Increased	Increased	Increased

The results of Table 9 reflect the spatial variability that is present in soils. Horizon depths are not uniform across a field. Also, in this study, inherent variability in the deposition and genesis of parent materials seems to be greater over a larger distance than in a smaller area. Beckett and Webster (1971) stated that over half of the variability existing in any field can be found in the first 1 m^2.

The challenge to the researcher is to be comfortable and confident that a sampling design encompasses a representative area of a particular field, both in properties and variability present. Statistical analyses must also be designed to account for this variability existing within a scale for study.

From the data of this study, a table was generated showing the approximate number of samples required to estimate the mean within 10% at a 95% significance level (Table 10). An example calculation for the Table 10 is included in Appendix A. In all cases, except bulk density, the number of samples required to estimate the mean increased as the sampling area increased for the sites and properties studied.

This table can provide a guide for assessing the transferability of data from site to site. In soils with similar variability, it should be expected that a similar number of samples are required to estimate the mean, characterize the variability, and to evaluate the subsurface

Table 10. Approximate number of samples required to estimate mean values within 10% at 0.05 significance level.

Property	Berwyn Grid	Berwyn Field	La Glace Grid	La Glace Field
Field MC	4	8	7	10
-33 kPa	2	5	2	5
-1500 kPa	5	10	5	7
AWHC	8	21	6	13
Sand	5	15	14	26
Silt	3	7	6	8
Clay	6	16	9	12
Bulk Density	10	5	6	2

lateral flow component with the same degree of confidence that was determined and used at the two study sites.

IMPLICATIONS OF SOIL PHYSICAL PROPERTIES TO FLOW STUDY

By characterizing the soil physical properties that have been identified as being important in both moisture redistribution and subsurface lateral flow, it should be possible to identify critical zones in the study site profiles. In the soil profiles at La Glace and Berwyn, soil properties were evaluated to a depth of 50 cm. These samples, within physical limitations, can be used to determine how the six soil properties identified change with depth.

Within the profiles, the strata of maximum variability have been identified. It will be assumed in this study that maximum variability corresponds to the profile depth to which pedogenic processes have progressed. These areas have been specifically identified for each soil and sample size. These transitions zones are deeper than normal cultivation depths and therefore it has been assumed that these zones are present because of soil genetic processes.

Results supported by Sichinga (1982) and Chanasyk and Woytowich (1983) indicated that 10-fold reductions with depth in hydraulic conductivity are present in some Peace River soils. Selected information from Chanasyk and Woytowich (1983) and from unpublished data for the study

site indicate that hydraulic conductivity does decrease by an order of magnitude with depth in the profile at both sites. Hydraulic conductivity data from 15 cm cores has been included in Appendix B. These hydraulic conductivity data indicate that the lower horizons of these soils should essentially act as impermeable, or slowly permeable barriers to moisture movement from the upper horizons.

Data for the soil physical properties in this study, when combined with those of Chanasyk (unpublished), show that these soils have a high water holding capacity, predominantly silt layer of moderately high hydraulic conductivity, over a denser, high clay content layer of lower hydraulic conductivity.

Therefore the results of this soil physical property study indicate that the potential for infiltrating water to be retained preferentially in the upper 10-25 cm of the soil profiles exists. This is primarily a function of water holding capacity, and/or the presence of an essentially impermeable lower horizon, or a profile discontinuity preventing rapid downward water percolation. Also, a preferential lateral movement of soil water could occur, as the upper horizon becomes saturated, due to the presence of the above factors combined with sloping soil surfaces, slope configuration, intense, short-duration precipitation events, or low evaporation periods during high moisture periods. In summary, this soil physical property study has identified specific strata or zones in the soil where subsurface

lateral flow should occur at the two study sites.

B. SOIL WATER STATUS STUDY

STATISTICAL DETERMINATION OF SUBSURFACE LATERAL FLOW

One of the initial objectives was that the experiment be designed so that the lateral flow component could be quantified. In this study the evaluation of the existence of a subsurface lateral flow component was determined statistically. Using the experimentally developed statistical grid design with replicated sampling, data were evaluated using ANOVA, as described in methods and materials. The statistical significance was tested by the F test at levels of 95 and 99%. The ANOVA's linear model symbols are described in methodology and more fully below. This model explains how the partitioning of the variability was interpreted in this study. The variable data used in the ANOVA was soil moisture content on a mass basis.

ANOVA Linear Model

Main Effects

A - Block - variation between two replicate units

B - Moisture - variation between the two treatments

C - Direction - variation among the two sets of two rings,

on the three directions specified

D - Distance - variation among the two sets of two rings with the four distances specified

Interaction Effects

BC - Moisture-Direction - variation in treatment in the three directions specified

BD - Moisture-Distance - variation in treatment with the four distances specified

CD - Direction-Distance - variation among the two sets of two rings using direction and distance criteria

BCD - Moisture-Distance-Direction - variation attributed to all three variables interacting simultaneously

E - Error - variation not attributed to any of the above effects

Significant (95% *) and highly significant (99% **) F values are marked in Tables 11 and 12. Specifically, this study focused primarily on main effect moisture, and on the interaction effects of moisture-direction and moisture-distance. A significant or highly significant F test with any of these effects was interpreted as confirmation that preferential moisture movement had occurred. This interpretation was justified since sampling was outside the infiltration ring and overland flow was not possible.

Table 11. ANOVA summaries of ring comparisons.

Depth	A	B	C	D	BC	BD	CD	BCD	Total
				Plot: La Glace Fallow					
0-5						**			1
5-10						**			1
10-15		*							1
15-20						*			1
20-25		**		*					2
25-30		**		*					2
30-35					*				1
35-40					*				1
40-45					*				1
45-50					*				1
Total	0	3	0	2	4	3	0	0	12
				Plot: La Glace Fescue					
0-5					*			**	2
5-10					**	**	*		3
10-15					*	**			2
15-20		*							1
20-25									0
25-30					**				1
30-35					**				1
35-40					**				1
40-45					**				1
45-50					*				1
Total	0	1	0	0	8	2	1	1	13

* Significant at 95%
** Significant at 99%

Table 11. ANOVA summaries of ring comparisons (cont'd).

Depth	A	B	C	D	BC	BD	CD	BCD	Total
Plot: La Glace Canola									
0-5						*			1
5-10						**			1
10-15						**			1
15-20						*			1
20-25						**			1
25-30						*			1
30-35	**	**		*					3
35-40	**	**							2
40-45						*			1
45-50					**	*			2
Total	2	2	0	1	1	8	0	0	14
Plot: La Glace Barley									
0-5						**			1
5-10						**			1
10-15						**			1
15-20		**							1
20-25		**							1
25-30									0
30-35									0
35-40	**								1
40-45	**								1
45-50	**								1
Total	3	2	0	0	0	3	0	0	8

* Significant at 95%
** Significant at 99%

Table 12. ANOVA summaries of ring comparisons.

Depth	A	B	C	D	BC	BD	CD	BCD	Total
Plot: Berwyn Canola									
0-5						**			1
5-10						**			1
10-15						**			1
15-20						**			1
20-25						**			1
25-30		*		*					2
30-35						*			1
35-40						*			1
40-45						*			1
45-50						*			1
Total	0	1	0	1	0	9	0	0	11
Plot: Berwyn Fescue 1									
0-5		**							1
5-10	*	**							2
10-15		**							1
15-20									0
20-25			*						1
25-30		**							1
30-35						**			1
35-40						**			1
40-45						**			1
45-50						*			1
Total	1	4	1	0	0	4	0	0	10
Plot: Berwyn Fescue 2									
0-5						*			1
5-10						**			1
10-15									0
15-20		*							1
20-25						*			1
25-30	**			*					2
30-35						*			1
35-40									0
40-45	*	*							2
45-50		*							1
Total	2	3	0	1	0	4	0	0	10

* Significant at 95%
** Significant at 99%

ANOVA and F test results were definitive. The previously specified null hypothesis was not accepted for 85% of the depths studied at both sites. Clearly, there was a change in water status with location after water had infiltrated. Moisture effect was significant or highly significant in 20% of the tests, moisture-direction in 32.5% and moisture-distance in 40%, at La Glace. At Berwyn, moisture effects were significant or highly significant in 26.6% of the tests, moisture-direction in 0% and moisture-distance in 56.6% (Tables 11 and 12). Overall, the effects of moisture, moisture-direction, and moisture-distance were significant or highly significant for 34 of the total 40 depths studied at La Glace and 25 of the total 30 depths studied at Berwyn.

A moisture-direction component did not exist at the Berwyn site, whereas it did at the La Glace site. Soils at La Glace, with a greater slope, therefore exhibited water movement in a preferential direction, while the soil moisture flow at Berwyn appeared to be moving laterally uniformly.

EVALUATION OF THE LATERAL FLOW COMPONENT

Using error mean squares from the ANOVA's, depths that were significantly different by the F test were again tested, using Duncan's NMR test at the 95 or 99% level to determine actual percent of moisture content change.

Calculations of lateral flow components are presented in Tables 13A and 13B. These flow components are the significant or highly significant flow values per depths, calculated as a percentage of total water added.

Moisture distributions with depth for the four different distances are given in Figure 8 for the fescue plot at La Glace. The fescue plot was chosen as an example because it is common to both sites. Calculations of the subsurface lateral flow component for this example are included in Appendix C. At a distance of 12.5 cm there is a highly significant increase in moisture content for the first depth increment. Graphically and statistically, it appears that retention of water is occurring at or above the 20 cm depth. This retention zone has been identified as being very important in the development of a subsurface lateral flow. Often such zones occur at a discontinuity in the profile, as identified in the soil physical property variability study. These discontinuities can influence both vertical and horizontal soil water movement. This process was diagrammatically represented and explained using Figures 4 and 5.

At La Glace (Table 13A), total depth cumulative flow components were 16.3% for barley, 25.1% for canola, 26.0% for fallow, and 8% for fescue. The overall average for the La Glace site was 18.8%. The Berwyn site had total depth cumulative lateral flow components of 21.3% for canola, 37.6% for fescue 1, and 9.8% for fescue 2, with an overall

Table 13A. La Glace lateral flow components.

Depth (cm)	Barley	Canola	Fallow	Fescue
	(% of total water added) *			
0-5	3.3	1.4	1.8	2.6
5-10	5.3	2.1	2.6	1.8
10-15	3.4	3.2	1.8	2.0
15-20	2.5	3.1	1.3	1.6
20-25	1.8	4.8	1.2	
25-30		3.4	2.2	
30-35		1.3	4.9	
35-40		1.5	9.2	
40-45		1.5	1.0	
45-50		2.8		
Total	16.3	25.1	26.0	8.0

* Significant at Duncan's 0.05 or 0.01

Table 13B. Berwyn lateral flow components.

Depth (cm)	Canola	Fescue 1	Fescue 2
	(% of total water added) *		
0-5	1.9	7.3	1.1
5-10	2.8	18.1	1.9
10-15	4.2	1.6	0.0
15-20	5.2	0.0	1.0
20-25	2.0	0.6	0.7
25-30	1.1	1.8	0.9
30-35	1.2	2.1	1.1
35-40	1.1	1.0	1.3
40-45	0.9	2.5	0.9
45-50	0.9	2.6	0.9
Total	21.3	37.6	9.8

* Significant at Duncan's 0.05 or 0.01

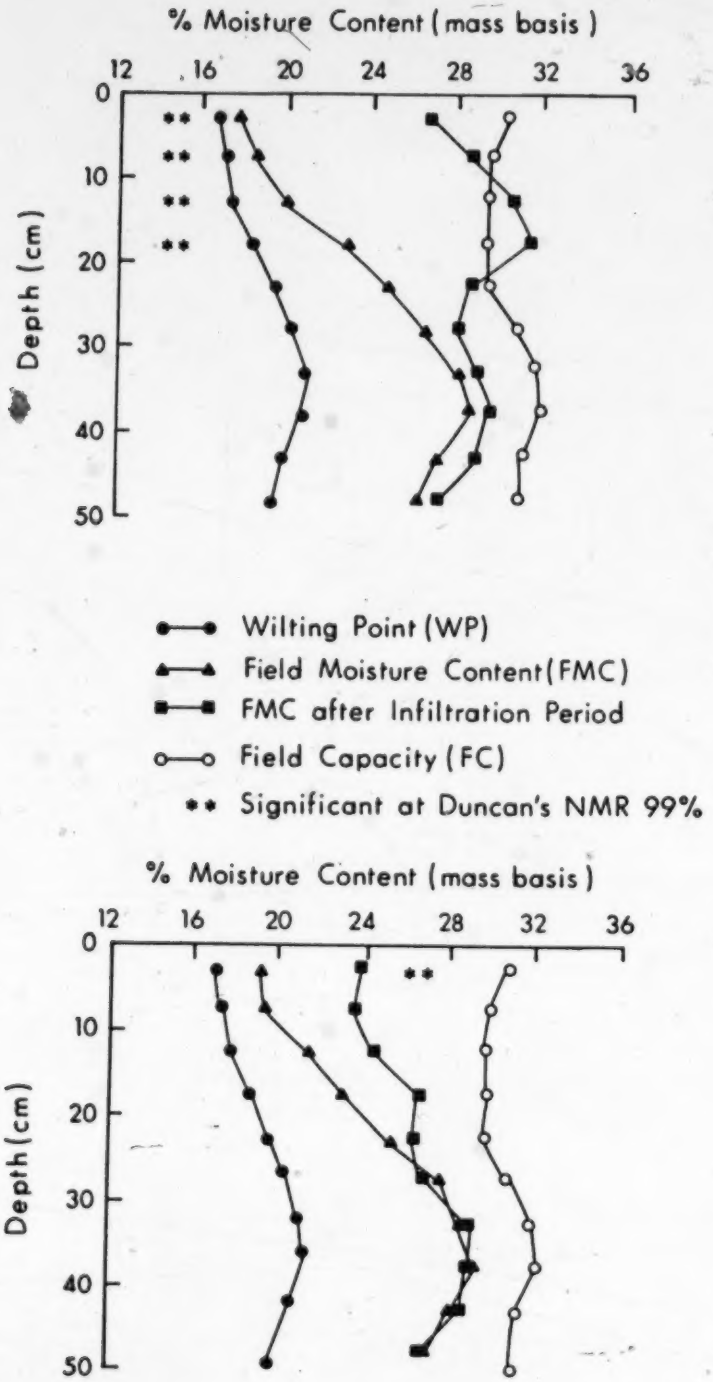
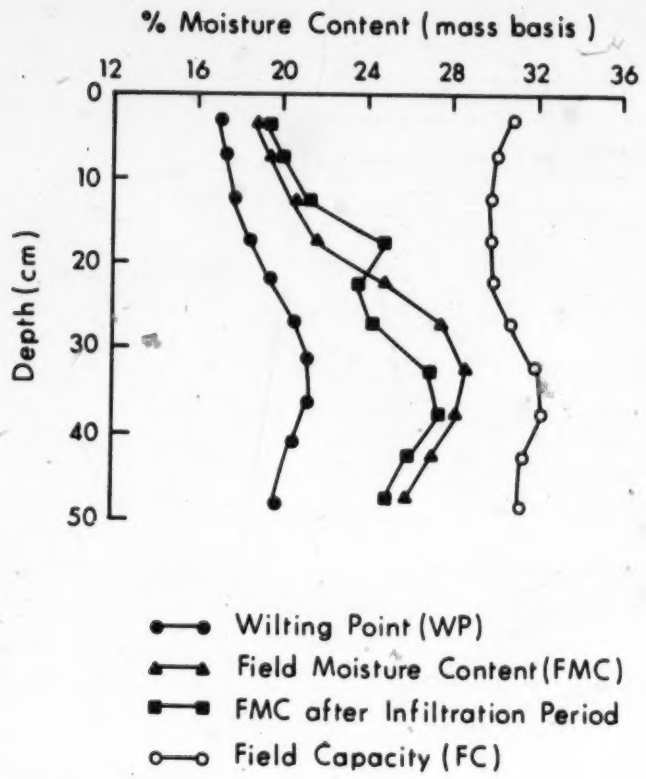


Figure 8. La Glace fescue plot water status study results at distances of 12.5 and 25 cm..



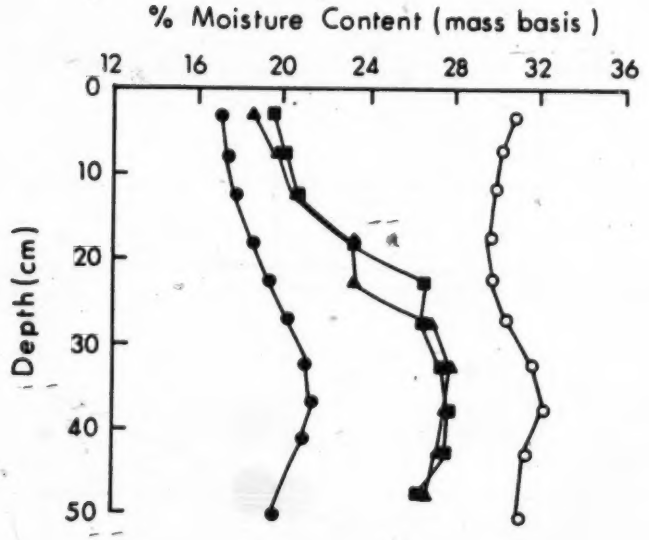


Figure 8 (cont'd). La Glace fescue plot water status study results at distances of 50 and 100 cm.

average of 22.9%.

The upper 20 cm of the profiles accounted for 53% of the total cumulative flow at La Glace, while the upper 20 cm at Berwyn accounted for 66% of the total cumulative flow. For both sites, the upper 20 cm was the maximum depth of the Ah horizon, and the strata that had the highest silt %, lowest bulk density and the greatest AWHC (Tables 3A, 3B, 5A, and 5B) as well as the zones that contained a discontinuity (Table 8).

The lateral flow components determined in this study were comparable to other results reported and reviewed in the literature review, ranging from 12% to 50% (Chanasyk, 1980).

The plots at Berwyn showed trends similar to those at La Glace (Table 13B). The canola plot showed a much greater lateral flow component than did the fescue 2 plot, with both plot values similar to those exhibited at La Glace plots. Berwyn plot fescue 1 had a relatively high lateral flow component, compared to the other plots. This high value appears to be related to two very high values in the top two depth increments. A possible explanation for these high values might be a temporary or perched water table that may have existed at the time of testing, or the presence of a large subsurface channel. No unusual values were noted in the physical properties for this plot. If these top two depth values are not considered, the cumulative lateral flow component became 12.3%, which is quite similar to the values

for Berwyn fescue 2 and those for the La Glace fescue plots. While statistical comparisons between sites were not possible because of the unreplicated plot design at each individual site, generally, it was noted that similar flow values were present at the two sites for similarly vegetated plots.

While this study focused on statistically substantiated quantification of subsurface lateral flow, a direct observation, important to the understanding and confirmation of flow processes, was made at the time of testing. Visual confirmation of a wetting front was possible at several of the infiltration ring sites at Berwyn. Subsurface lateral flow was also observed after an intense, short duration rainfall event (approximately 4-5 cm in a 30 minute period). After a short period of approximately five minutes, both surface and subsurface flow were observed in the flume system of the soil erosion runoff plots. Flow rates on these 2% sloped plots was up to 200 L min^{-1} at peak flow. Interestingly, and relevant to this study, after surface runoff had stopped, subsurface flow continued for approximately 10 minutes. Soil moisture content samples taken at this time confirmed that the majority of the moisture was restricted to the upper 25 cm of the profile. It appears that the vast majority of the rainfall quickly created a saturated temporary perched water table in the top 25 cm of the profile, then ran laterally via both a surface and a subsurface route. If the rainfall event could have

been experimentally controlled, it would have been interesting if the critical infiltration rate could have been maintained without causing overland flow. Although the evidence was qualitative, observation of this rainfall event confirms many of the processes that have been alluded to and hypothesized by this study.

EFFECT OF INITIAL MOISTURE CONTENT

This study was conducted at only one narrow moisture content range. Any development of soil water flow processes from this study must address whether flow values would be similar under other moisture contents. Hydraulic conductivity increases as initial moisture content increases, and infiltration rate decreases as the soil moisture content increases. Therefore, it follows, the wetter the soil, the faster the water will move through the soil, but the slower it will enter. Therefore, two main situations can arise: First, the soil could be saturated, perhaps at spring thaw or after a large precipitation event. Any additional water to this system would be very slow to infiltrate, and if it did, it would probably flow laterally, if soil slope and profile characteristics were conducive to subsurface lateral flow. Secondly, if the soil was very dry, hydraulic conductivity would be very low, but infiltration rate would be high. If the rainfall event was well below the critical infiltration rate, then water would readily

infiltrate, and percolate into the profile, until the soil surface became saturated, or nearly saturated. Either the entire profile would be saturated, or the profile would be saturated upwards from a discontinuity. When the upper portion of the profile became saturated, then this situation becomes similar to the first case, with the same result. However, if the rainfall event was very intense, a dry soil could quickly result in infiltration rate exceeding hydraulic conductivity rate, resulting in a perched or temporary water table forming at a discontinuity or near the surface. The result of this case would be either large values of the lateral flow, or if the precipitation event was large enough, overland flow and subsurface lateral flow. This last case was probably the situation encountered in the Berwyn rain storm.

Within limits, initial moisture content is important to subsurface lateral flow values. During periods of high initial soil moisture content, high levels of both overland and subsurface lateral flow could be expected. During periods of relatively dry initial moisture contents (similar to field moisture contents of this study) larger precipitation events would be required to either saturate the profile, or to create a temporary water table at discontinuities before subsurface lateral flow, and possibly overland flow, would occur. It follows that the values achieved in this study are probably relatively low flow values, compared to flow during periods of high initial

moisture content.

COMPARISONS OF PLOTS AND VEGETATION

Due to the preliminary nature of this study, the objectives, experimental design and hypotheses did not include evaluations of the vegetation between plots and between site variables. While statistically valid comparisons between various vegetation types and plots seem scientifically desirable, experimental design and ANOVA evaluation of these variables were not possible. Such comparisons are not statistically valid in this design because of an unreplicated vegetation variable. Any conclusions of differences in lateral flow rates due to different vegetation would simply be conjecture if based on this study's data.

Now that preliminary and baseline data have been established, a comparative study on how vegetation affects subsurface lateral flow rates seems like an informative and complementary extension of the first study. The vegetation effect on flow rate information would be highly desirable in soil erosion-runoff control management systems, if different lateral flow rates occur under different vegetation.

V. CONCLUSIONS

The variability of soil physical properties increased with the size of the area sampled for all properties studied, except for field moisture content. When complemented with soil physical property values that are similar in variation to those evaluated in this study, similar lateral flow components could be expected in other Peace River soils.

The existence of a significant subsurface lateral flow component was confirmed at both study sites. The null hypothesis of no significant difference in water status with location was not accepted at 85% of the depths studied. The soils at La Glace exhibited a moisture-direction and moisture-distance component, while soils at Berwyn exhibited a moisture-distance component. An average 18.9% subsurface cumulative lateral flow component was calculated for La Glace, while the average cumulative flow component at Berwyn was 22.9%. The % of the total subsurface flow that occurred in the upper 20 cm of the profiles were 53 and 66% at La Glace and Berwyn, respectively.

Extrapolating the results of this study to a precipitation or springmelt event, it should be expected that at least 50% or more of the moisture infiltrated would be retained in the upper 20 cm of the profiles of these two soils. The soil water would begin moving laterally in the subsurface zone, as the pressure head increased from

upslope, and the moisture in the soil reached retention capacity.

Many soils in the Peace River region have high silt contents and horizons of high clay content at depth. When these characteristics are combined with slope and vegetative conditions conducive to flow, the potential for significant subsurface lateral flow exists. In this study, for the given moisture conditions, approximately 19 to 23% of all flow was via a subsurface lateral flow route. Under saturated conditions, either during springmelt or after long duration precipitation events, the lateral flow component would probably be much greater.

The results reported in this study should be transferable and similar to other sites and soils in this region, given similar variability and site characteristics.

VI. PRACTICAL APPLICATIONS AND ADDITIONAL STUDIES NEEDED

From the information gathered at the two study sites, it appears that soil management can take two directions; either through managing the top 20 cm of soil, or attempting to change or modify the soil below this depth through drainage or disruption of the B horizon.

This study found that 53 and 66% of the water added at La Glace and Berwyn, respectively, was retained in the upper 20 cm of the profile, and that 19-23% of this water moved laterally via a subsurface route, given similar moisture conditions. Secondly, the high % clay, high density, low hydraulic conductivity B horizon prevented the rapid drainage of water.

From a soil water erosion prevention viewpoint, the top 15-20 cm surface horizons of these soils are susceptible to water erosion, because they are weakly aggregated, have a high % of silt, and are high moisture capacity soils on sloping surfaces. Practices to prevent soil water erosion must concentrate on: 1) securing the top 20 cm of the soil to the B horizon with compatible vegetation, 2) facilitating rapid drainage of excess water from this top zone via mechanical, cultural or integrated vegetative systems, 3) prevention of accumulation of large amounts of moisture via cultural practices, and 4) modification of the A-B horizon interface.

Prevention of soil erosion on Peace River soils requires an integrated management system using soil-plant-water interactions and fundamental physical laws of soil water flow simultaneously. The integrated management system must facilitate rapid removal of excess water from the soil surface and surface horizon. Methods used to retain water in place and promote water accumulation on saturated slope surfaces could possibly result in larger incidences of rill or sheet erosion of these soils.

A possible integrated management system to prevent soil water flow and soil erosion could contain several of the following aspects: a cropping system that promotes thick, densely rooted crops, leaving large portions of stubble standing, but cut relatively short to prevent snow accumulation; with an integrated drainage system of contours, ridges, and surface drains on sloped land leading to grassed waterways to remove surface water. Deeply ripped cross-slope surface intercept strips or a very well maintained lateral subsurface interception drainage network could be feasible in preventing water erosion on susceptible soil surfaces by reducing excess subsurface lateral flow.

From a soil-plant management point of view, the Peace River region is suited to growth of annual and perennial crops that have thick, dense surface rooting habits, combined with deeply penetrating roots. Cultural practices should encourage fertilizer placement in the top 20 cm, to stimulate root proliferation in this zone to secure soil and

assist with water removal from this susceptible zone. Plant breeding should concentrate on possible development of plants that show proliferation of dense, relatively short, strong, root systems.

The above recommendations are written from a soil conservation and integrated management viewpoint. They have not been scientifically proven, nor has this system been completely balanced for the agronomic needs of crop management, seed bed preparation, timeliness of crop planting, or as the system for achieving maximum economic yields. Further studies are required to assess the practicality of implementing an integrated soil-water-plant cultural system to prevent soil erosion and to manage soil water flow, while achieving successful agronomic objectives.

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VIII. APPENDIX A

Calculation of number of samples required to estimate within 10% of mean: Berwyn field moisture content means.

Formula

$N = t^2 \sigma^2/D^2$ where N = number of samples required, t = Student's t with (n-1) degrees of freedom at the probability level α, σ^2 = the total variance of the parameters, and D = specified limit.

Sample Calculation:

D = 10%

α = 0.05

Field mean value of 36 samples/depth, averaged over 10 depths = 17.01

10% specified limit of field mean for FMC = 0.10 x 17.01 = 1.701

$t\alpha$ for 35 degrees of freedom, at 95% level = 2.03

σ^2 for FMC, average of 10 depths = 2.27

$$N = \frac{(2.03)^2 \ (92.27)^2}{(1.701)^2}$$

N = 7.34

therefore N = 8 samples

IX. APPENDIX B

Table 1. Hydraulic conductivity data.

Berwyn site

Depth (cm)	Test 1 (cm s^{-1})	Test 2 (cm s^{-1})	Test 3 (cm s^{-1})
0-15	3.33×10^{-5}	5.12×10^{-5}	2.57×10^{-5}
15-30	5.84×10^{-5}	2.97×10^{-5}	3.56×10^{-5}
30-45	7.91×10^{-6}	1.42×10^{-7}	4.41×10^{-5}
45-60	2.73×10^{-6}	1.33×10^{-6}	3.92×10^{-6}

La Glace site

Depth (cm)	Test 1 (cm s^{-1})	Test 2 (cm s^{-1})	Test 3 (cm s^{-1})
0-15	5.7×10^{-5}	1.4×10^{-5}	5.7×10^{-5}
15-30	2.0×10^{-6}	2.3×10^{-7}	4.5×10^{-5}
30-45	9.0×10^{-7}	1.0×10^{-7}	9.0×10^{-6}
45-60	1.4×10^{-6}	1.9×10^{-8}	6.2×10^{-7}

Test 1 - field scale - medians of 8 samples
Test 2 - medians of 4 samples (south and east of the erosion plots)
Test 3 - medians of 2 samples (close to the canola plot)

X. APPENDIX C

Table 1. Sample calculation of lateral flow component.

Plot: La Glace								
Depth (cm)	Distance Means (cm) 12.5	25	50	100	12.5	25	50	100
0-5	1**	2**	3	4	5	6	7	8
5-10	1**	2	3	4	5	6	7	8
10-15	1**	2	3	4	5	6	7	8
15-20	1**	2	3	4	5	6	7	8

** significantly different at 0.01 using Duncan's NMRT
EMS for each depth is calculated from matrix
Distance 1-4 wet ring 5-8 dry ring

Table 2. Difference in field water content: dry vs wet.

Depth (cm)	Wet (%mass)	-	Dry (%mass)	=	Change (%mass)
0-5(1A)	26.87	-	17.79	=	9.08
0-5(1B)	23.83	-	18.88	=	4.95
5-10(2A)	28.84	-	18.87	=	9.97
10-15(3A)	30.71	-	19.99	=	10.72
15-20(4A)	31.17	-	22.95	=	8.22

1A = 0-5 cm depth, 12.5 cm distance
1B = 0-5 cm depth, 25 cm distance
26.87 is mean at distance 12.5 cm from ring
(mean of two rings/3 values per ring)

Table 3. Calculation of lateral flow as % of total water added.

1. Soil volume x bulk density = soil mass
2. Soil mass x change = mass water (% mass basis)
3. Mass water ÷ total H_2O added (90 000 g) = % of total H_2O added

Depth cm	Change %	Bulk Density Mg m^{-3}	Soil Volume cm^3	Soil Mass g	Mass Water g	% of Total
0-5(1A)	9.08	1.06	14235	15089.1	1370	1.52
0-5(1B)	4.95	1.06	19144	20293.0	1005	1.12
5-10(2)	9.97	1.10	14235	15659.0	1561	1.74
10-15(3)	10.72	1.16	14235	16513.0	1770	1.97
15-20(4)	8.22	1.22	14235	17367.0	1428	1.59
				Cumulative Total		7.94